

HANDBOOK OF SCIENCE AND TECHNOLOGY STUDIES



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Engineering Studies

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PERHAPS the most significant contribution of research in engineering studies is that it provides case studies of life on the constructed social boundaries between science and society and between labor and capital. Engineering knowledge, for example, appears to be neither purely scientific nor only social but somehow a combination of the two. As the term *applied science* has long suggested, albeit misleadingly, knowledge-producing activities in engineering appear to occupy a double location both inside and outside of science. At the same time, engineering work appears somehow to be a combination of the activities of labor and the activities of capital. In positions that vary from country to country, engineers regularly find themselves grappling with ambiguities engendered by their double location as both objects and representatives of corporate power. The ambiguities in engineering knowledge and engineering work thus not only raise interesting conceptual problems about boundaries but also generate difficult power issues for engineers as persons.

Most of the differences within engineering studies derive from contrasting interpretations of these boundary locations. In this review, we take characterizing the different interpretations as our primary task, with the goal of bringing them into more productive dialogue. Our central argument is that,

by throwing into question the conceptual status of the science/society and labor/capital boundaries while exploring the implications of those boundaries for engineers, engineering studies provide fertile ground for exploring and documenting diversities both within and between science and capitalism.

We bound our work in several ways. First, we focus on studies that interpret how engineers understand and do engineering. That is, rather than beginning with a definition of engineering knowledge or engineering practice and then looking for research that falls within that definition, we approach engineering as a cultural activity done by engineers and look for research that offers interpretations of engineers doing engineering. We thus position our field of vision around practicing engineers and limit our attention to work dealing with roughly the last 200 years. We do not inquire into the practices of Renaissance artisans or into post-Galilean, pre-industrial revolution negotiations between science and technology.

Second, despite declining to offer essentialist definitions of engineering, we distinguish engineering studies from technology studies, partly because this volume includes chapters on technology studies and partly to illustrate the conceptual point that demarcationist strategies are contingent acts of positioning. Just as we believe that extrapolating science forward into applied science does not capture sufficiently what engineers understand engineering to be about, neither does reasoning backward from technology into technological knowledge and design. Our contingent purpose in distinguishing engineering studies from technology studies is to enhance the comparative dialogue among studies of engineering.

Third, we confine our interests to work published since 1980, with a few exceptions. One of us has coauthored an essay that examines pre-1980 work in some detail (Downey, Donovan, & Elliott, 1989). As that essay argues, until roughly the last decade, the boundary location of engineering provided sufficient reasons for most scholarship in STS disciplines to ignore engineering, or at least to view it with yawns assertive enough to scare off untenured professors and most anyone else who did not revel in intellectual marginality and conceptual insignificance. Many scholars attempted to establish subdisciplinary traditions of inquiry into engineering, but these were generally unsuccessful. By repeatedly encountering conceptual problems that fell outside of disciplinary categories of analysis, such work typically found itself marginalized from disciplinary activities.

Fourth, we focus on empirical studies of engineering. In our judgment, further conceptual advancement in engineering studies depends critically upon continued, indeed accelerated, growth in the corpus of empirical work. So many surfaces have only been scratched.

The review is divided into four sections: engineering knowledge, engineering as technical work, gender studies, and studies by engineers. With these

distinctions, we hope to help those of you whose interests are confined to certain areas, although take note that many studies cut across these boundaries. At the same time, these distinctions highlight what we think should be a central goal in the next generation of engineering studies: accounting for the interrelations among knowledge and power in engineering.

ENGINEERING KNOWLEDGE

Virtually all inquiries into engineering find some conceptual position for the content of engineering knowledge. This is no easy task, for the traditional model that devalues engineering knowledge as simply applied science (see Boorstin, 1978; Dorf, 1974; Lawless, 1977) is always present staring one in the face, challenging detractors to come up with equally clean alternatives. Much research explicitly focused on engineering knowledge has sought, in fact, to show that engineering does not simply involve the application of science to produce technology but has independent content. Researchers position themselves at various points around the question: How should one account for the distinction between engineering science and engineering design?

A 1955 committee of the American Society for Engineering Education classified the engineering sciences into six categories: (a) mechanics of solids, including statics, dynamics, and strength of materials; (b) fluid mechanics; (c) thermodynamics; (d) rate mechanisms, including heat, mass, and momentum transfer; (e) electrical theory, including fields, circuits, and electronics; and (f) nature and property of materials. This ASEE classification had a political dimension: It helped to legitimize educating engineers in each of these sciences beyond the "basic" sciences of chemistry, physics, and mathematics. In parallel fashion, most studies of the engineering sciences have distinguished them from the natural, physical, and biological sciences, claiming engineering science to be a distinct species of science. This "demarcationist" approach has served the important political goal of legitimizing direct scholarly attention to engineering.

The bulk of demarcationist work has been produced by historians of technology, for whom specifying in detail the character of technological knowledge has also helped to legitimize the history of technology as an independent activity alongside the history of science. The guiding spirit in this movement has been Edwin Layton. Ever since his 1971 article, "Mirror Image Twins: The Communities of Science and Technology in 19th-Century America," Layton has systematically defended what, following Barnes (1982a), he calls the "interactive model" of science and technology (Layton, 1971, 1974, 1976, 1984, 1987, 1988a, 1988b).

As a mirror-image twin of science, technology is "an autonomous, coequal community" whose relationship with science is "symbiotic, egalitarian, and interactive" (Layton, 1987, p. 598). Engineers are interesting in this model as the quintessential holders of technological knowledge, represented by the engineering sciences. According to Layton, the engineering sciences come in "two somewhat different types": (a) the "less idealized natural sciences," such as fluid mechanics, which transformed the empirical science of hydraulics by incorporating the study of viscosity, and (b) sciences that seek "to gain a scientific understanding of the behavior of man-made devices," such as portions of thermodynamics that advance idealized models of heat engines (Layton, 1984, p. 10; see also Böhme et al., 1978, p. 240).

While Layton has been the most persistent, the most thoroughgoing attempt at detailing the epistemological content of engineering science is found in the work of Walter Vincenti (1979, 1982, 1984, 1986, 1988, 1990). Viewing theoretical knowledge as a component of engineers' design knowledge, Vincenti (1990, pp. 207-224) adds to Layton's distinction on the one side purely mathematical methods and theories, ranging from analytical geometry to computer algorithms, and on the other side a cluster of device-related theoretical tools, including device-specific approximations (beam theory, modeling of transistors), phenomenological theories (modeling of turbulent flow), and quantitative assumptions (how rivets share loads).

Some studies have explored the genesis and early development of the engineering sciences in the nineteenth century. David Channell (1989) offers a comprehensive bibliography of core works and historical materials on applied mechanics, thermodynamics and heat transfer, and fluid mechanics. Channell (1982, 1984, 1986, 1988) also describes how Rankine consciously positioned engineering science between theory and practice during the mid-nineteenth century "in such a way that it would not threaten scientists, and . . . would avoid any competition with the offices of civil engineers, or the workshops of the mechanical engineers, or any interference with the usual practice of pupilage or apprenticeship" (Channell, 1982, p. 45). In his first call for investigations of technological testing, Edward Constant (1983) shows how the development and use of dynamometers to test water turbines contributed to the development of engineering science by relating scientific theory to waterpower practice. Eda Kranakis (1982) argues that grappling with conceptual anomalies in the injector, a nineteenth-century device for supplying water to steam engines, provided key contributions to the development of engineering thermodynamics. Ronald Kline (1987) explores how electrical engineers transformed Maxwell's electromagnetic theory in order to construct an engineering theory of an electromechanical device, the induction motor. Finally, Rosenberg and Vincenti (1978) outline the development of the method of parameter variation; Vincenti (1982), the development

of control volume theory; and Layton (1988b), the development of the use of dimensionless parameters.

Other studies have explored interactions during the twentieth century between engineering theory and either science on the one side or design considerations on the other. Terry Reynolds (1986) describes the development of chemical engineering by exploring the efforts of production chemists to distinguish their knowledge from analytical chemistry. Bruce Seely (1984, 1988) examines the failed attempt by highway engineers to reconstruct highway research entirely in scientific terms during the period of proscience euphoria following World War I. By tracing the career of Irving Langmuir at General Electric Company, Leonard Reich (1983) details the boundary problems of industrial researchers, who find themselves to be neither scientists nor engineers yet both at the same time. In a reversal of the normal flow of theory from science to engineering, Joan Bromberg (1986) describes how, by applying circuit analysis to understand lasers, electrical engineers both provided conceptual help to physicists and generated boundary problems in their careers.

Several "internalist" histories have appeared that detail the evolution of engineering theories. For example, Stephen Timoshenko (1953) examines theories of strength of materials; Issac Todhunter (1960), theories of elasticity in relation to strength of materials; T. M. Charlton (1982), the theory of structures; and Donald S. L. Cardwell (1971), theories in thermodynamics. For a multitude of other works that conduct more limited forays into engineering science as a subset of technological knowledge, we also direct your attention to reviews by Staudenmaier (1985), G. Wise (1985), and A. Keller (1984), the symposium collection in Sladovich (1991), and to articles and books reviewed in the journal *Technology and Culture*. Finally, see Reynolds (1991) for an excellent comprehensive collection on the history of engineering practice and institutions.

Another source of demarcationist accounts is the philosophy of technology, which has sought to discern cognitive structuring in engineering theory at least since the 1966 debate among Mario Bunge, Joseph Agassi, and Henry Skolimowski over whether technology should be understood as applied science. In that debate, Bunge (1966) drew a sharp line between pure and applied science; Agassi (1966), between applied science and technology; and Skolimowski (1966), between science and social practice. As starting points for pursuing the study of engineering science further into the philosophy of technology, we suggest Michael Fores's (1988) critique of the concept of engineering science with responses by Layton (1988a) and Channel (1988), Joe Pitt's (n.d.) forthcoming theory of technology, the review in Downey et al. (1989), and annual issues of *Research in the Philosophy of Technology*. Finally, one philosopher of science, Ronald Laymon, has sought to examine

the conceptual structure of engineering science. In an interesting account, Laymon (1989, pp. 353-355) examines engineers' strategies for using "idealization" to "manage [the] unavoidable complexity" that comes from applying scientific theories to design problems.

Research on engineering design has been more diverse, divisible into roughly three camps: demarcationist, constructivist, and actor-network interpretations. Each camp offers distinctive approaches to understanding the role of visual representations in engineering knowledge and practice.

A leader again among the demarcationists, Vincenti (1990, pp. 207-225) identifies five more categories of design knowledge beyond the theoretical tools described above. These include (a) fundamental design concepts defined in engineering terms, such as the central operational principles of static structures (bridges) or dynamics machines (aircraft); (b) criteria and specifications, such as those embodied in engineering standards; (c) quantitative data, including physical constants, properties of materials, and safety factors; (d) practical considerations, such as knowledge gained from accidents; and (e) design instrumentalities, including structured procedures and optimization strategies. In aesthetic approaches to demarcationism, David Billington (1979, 1983) argues that engineering structures have distinctive aesthetic characteristics, and Baynes and Pugh (1981) elaborate what they call the art of engineers. Finally, E. Ferguson (1992) critiques the twentieth-century replacement of visual knowledge in engineering with analytical knowledge.

Constructivist studies describe the design methodologies of engineers as shaped in various ways by social considerations. For example, Louis Kemp (1986) documents the aesthetic contributions of city planners to the design methodologies of highway engineers. Larry Owens (1986) explores Vannevar Bush's early work on the differential analyzer and how "[it] embodied an engineering culture belonging to the first decades of our century" (p. 95). L. L. Bucciarelli (1988) describes the engineering design process as an endless series of iterative loops as engineers respond to ever-changing problems and situations. Frederick Lighthall (1991) accounts for the failure of Morton Thiokol engineers to predict O-ring failure on the *Challenger* to insufficient training in statistical methods. Diana Forsythe (1993a, 1993b) examines the cultural construction of "knowledge engineering," the practice of transferring knowledge from experts to expert systems. Gary Downey (1992a, 1992b, 1992c, in press-a) shows how developers of CAD/CAM technologies (computer-aided design and computer-aided manufacturing) endow the technologies with agency by "transcribing" the activities of design engineers into computer code and then transforming those activities by inserting the technologies back into them as participants.

Finally, actor-network studies (see elsewhere in this volume) describe the activities of engineering design as situated practices that have both technical

and nontechnical content and that combine to build networks of conceptual and political power. John Law's term *heterogeneous engineering* (Law, 1986b, 1987a, 1987b) encapsulates this dual conceptual and political point, for it claims simultaneously that all engineering is the product of heterogeneous factors and considerations and that all design activities in technology are forms of engineering. Michel Callon (1980a, 1980b, 1986a) initiated this line of argument with regard to engineers by describing how French engineers designing an electric vehicle simultaneously constructed the entire infrastructure within which the vehicle would work. Law and Callon (1988, p. 284; see also Law, 1988) also argue that engineers are "engineer-sociologists" in that they are "not just people who sit in drawing offices and design machines" but are "social activists" who design societies or social institutions to fit the machines. These latter claims draw inspiration, in part, from Langdon Winner's (1986b, pp. 19-39) arguments that technical manuals or designs for nuclear power stations imply conclusions about the proper structure of society, the nature of social roles, and how these roles should be distributed.

In other actor-network interpretations of engineers, Bruno Latour (1987, p. 104) reinterprets Lynwood Bryant's (1976) account of the development of the diesel engine by tracing Rudolf Diesel's early successes and later failures in building links to Carnot's thermodynamics, investors, and potential users. Susan Leigh Star (1990) accounts for how engineers use CAD (computer-aided design) programs to design computer chips by chronicling the tensions between CAD representations, "which are static and abstract," and engineering work, "which is real-time and concrete" (p. 128). Finally, Kathryn Henderson (1991a, 1991b) describes the visual communication practices of engineers by focusing on how engineering drawings and computer-aided design programs function as "conscription devices" that socially organize both workers and the structure of work.

One likely growth area that involves both engineering science and engineering design are new approaches to the knowledge content of engineering education. Noble's (1977) classic argument describes both the form and the content of engineering education unilinearly as "a major channel of corporate power" by providing the "immediate manpower needs of industry and the long-range requirements of continued corporate development" (pp. 47, 170). Carlson's (1988) study of academic entrepreneurship at MIT argues, however, that corporations "could not simply order entry-level engineers from engineering schools," and linkages between engineering education and industry were "marked by a clash of values and expectations" (p. 396). Similarly, Downey (in press-b) finds a "theoretical space between the notions of engineering control and corporate control" to show how engineering curricula empower engineers by shifting them to the boundary between humans

and machines. In forthcoming work from a 3-year study of how engineering education constructs engineers as persons, Downey, Hegg, and Lucena (in press) show how the knowledge content of engineering problem solving generates identity conflicts according to gender, race, and class characteristics.

ENGINEERING AS TECHNICAL WORK

Over the past 10 years, as Chris Smith (1991) points out in a review essay, "there appears to have been a veritable explosion of interest in technical labour" (p. 452). Inquiries into engineering as a form of technical work generally focus on the social mechanisms and processes that shape and position engineers as workers. Excellent reviews by Peter Whalley (1991) and by Peter Meiksins and Chris Smith (1991) identify many of the changing issues and trajectories of research. A significant shift in emphasis has taken place from a focus on engineers as professionals to analyses of the class character and implications of engineers working in industrial organizations. Whereas the first, as Whalley (1991, p. 193) succinctly puts it, has been "largely Anglo-American and Weberian in influence," while the second has been "European and Marxist," the most significant recent trend has been a multiplication of class-based accounts. One of the most promising outcomes is a strong commitment to cross-national comparison.

From the 1950s through the mid-1970s, researchers typically took for granted the engineer's status as an autonomous, or free, professional akin to professionals in law, theology, and medicine and looked for answers to the functionalist question: What happens to professionals who work in organizations? When the answer that eventually emerged was that engineers were a different type of professional—that is, organizational professionals—the effect was to undercut the functionalist study of professions (see Downey et al., 1989, for a detailed account of work in the United States). At that time, however, as Whalley (1991) elaborates, a new sociology of professions developed with the goal of accounting for their autonomy and high class position. This perspective drew on the Weberian argument that one's position in the class structure depends upon the marketable skills that one possesses. Accordingly, it viewed professions as occupations whose possession of scarce and important knowledge enabled them to build power for themselves, effect closure, and achieve autonomy and high class status.

Developing alongside the sociology of the professions, Marxian accounts have treated engineers entirely in class-based terms. Prior to the 1970s, most Marxian studies described engineers as populating that part of the working class that was white collar, received high salaries, and was close to management. One strain of thought that developed among French sociologists, most

notably Serge Mallet (1975), held that technical workers were part of a "new working class" that had potential for radical action. However, rapid growth in the number of such technical workers cut against the accompanying "proletarianization thesis" (Braverman, 1974), which held that white-collar workers were being "deskilled" and would be forced to merge with a growing proletariat (Whalley, 1991, p. 196). The key conceptual problem for Marxian analysis became how to account for a growing middle class of workers.

The Weberian and the Marxian accounts of engineers have thus converged on the problem of accounting for the ambiguous, middle-class character of engineers as technical workers. A key contributor to the rise of interest in the class characteristics of engineers was a large comparative analysis of engineers in three industrialized countries, carried out by three graduates of Columbia University under the supervision of Allan Silver: Peter Whalley (1984, 1986, 1987, 1991) in Great Britain, Robert Zussman (1984, 1985) in the United States, and Stephen Crawford (1989, 1991) in France. The original objective was to assess the implications of an international shift to a post-industrial economy built on knowledge-based industry. However, comparing the work and statuses of engineers in low-tech industrial companies with those in high-tech, knowledge-based companies, each study actually defuses the question of postindustrialism by finding little difference between the two. Rather, by documenting the varying class experiences of engineers in different national contexts, the case studies highlight contrasts in national traditions and focus attention on cross-national comparison as a method for formulating and evaluating alternative accounts of the class characteristics of engineers.

Understanding the contrasting national experiences of engineers can also help one to understand contrasting national patterns of research on engineering as technical work. The bulk of research on the role of professionals in organizations has been conducted in the United States, where the "professional" has perhaps been institutionalized most strongly as an occupational classification (Whalley, 1991, p. 202). That is, in the structural tension between workers and management, engineers clearly fall on the side of management. The Wagner and Taft-Hartley acts made them exempt from collective bargaining laws, and, armed with university training and credentials, they serve as technical specialists within corporations. Also, engineers in the United States have organized themselves into professional associations, although it is significant that these do not exclude corporate interests from their definitions of professional interests.

For example, in his republished *Revolt of the Engineers*, Edwin Layton (1986) traces how corporate-minded conservative elites in the early twentieth century succeed in overcoming attempts by profession-minded elites to establish engineering as an autonomous profession. This work established

professional societies as a privileged site for tracing the political orientations of American engineers and the development of engineering as a profession (e.g., Downey et al., 1989, pp. 207-208; McMahon, 1984; Reynolds, 1983; Sinclair, 1986). Histories of engineering education in the United States also concentrate on the professional development of American engineers (Bezilla, 1981; Gordon, 1982; McMath, 1985; Ochs, 1992; Wildes & Lindgren, 1985). Trajectories of research in management studies, especially studies of "organizational culture," tend to focus on tensions between the individual professional orientations of engineers and the organizational orientations of their employees (Bailyn, 1980, 1985; Bailyn & Lynch, 1983; Kunda, 1992; Raelin, 1986). An extensive philosophical literature in engineering ethics seeks to enumerate ethical principles to guide engineers, given their status as professionals in organizations (e.g., Baum, 1980; Baum & Flores, 1980; Davis, 1991; Downey et al., 1989, pp. 202-203; Flores, 1989; Johnson, 1989; Layton, 1985; Martin & Schinzinger, 1989; Schaub & Pavlovic, 1983; Unger, 1982, 1989). Finally, the role of the military in shaping American engineering and the contemporary implications of post-cold war conversion strategies deserve radically expanded attention (e.g., Markusen & Yudken, 1992).

Yet the rise of interest in class is evident. Presenting the Marxian view that labor and capital stand in structural opposition, David Noble (1977, 1979, 1984) details histories of American engineers as domesticated servants of capital while Donald Stabile (1984) uses the experiences of mechanical and industrial engineers during the early twentieth century to describe engineers as situated in a contradictory position between labor and capital. In a Weberian account, Robert Zussman (1984, 1985) argues that the occupational identities of engineers are better understood by examining their trajectories through "careers." That is, the collective product of engineers' careers and their family lives in single-family dwellings and in neighborhoods alongside workers is a "working middle class," a notion that directly challenges the Marxian opposition.

Finally, in an interesting body of work on American engineers, Peter Meiksins has been a thoroughgoing proponent of a shift from profession to class. In survey research with James Watson, Meiksins argues that engineers are concerned less with professional autonomy than with the technical content of their work, concluding that researchers "need to shift the focus of research away from issues such as professional autonomy toward the nature of engineering work itself" (Meiksins & Watson, 1989; Watson & Meiksins, 1991, p. 165; see also Meiksins, 1982). Reconsidering the revolt of the engineers through a detailed case study, Meiksins (1986, 1988) explains the rise and fall of the American Association of Engineers during the early 1920s as the product of an alliance between elite progressives and rank-and-file engineers that dissolved for class reasons (see Sinclair, 1986, for another call

to study rank-and-file engineers). Finally, in recent collaboration with Chris Smith (Meiksins & Smith, 1991, in press; Smith & Meiksins, 1992), Meiksins details the class characteristics of American engineering in comparative perspective.

In Great Britain, engineers have positioned themselves as higher status craft workers rather than as managers with autonomy. British companies have given little attention to professional credentials; the state has played a small role in engineering education; and engineers opt for unions rather than professional organizations. Success in engineering work has been based more on the acquisition of technical skills than on science-based education, producing a system that is now challenged by the expansion of high-technology industry. Yet, despite their comparatively low status (for a history of the status of engineers in Great Britain, see Buchanan, 1983), engineers have remained concerned in varying ways and at varying times with the possibilities and ambiguities of professional status.

Much of the research on British engineers has been, and continues to be, engaged with the problematic of professionalism. For example, historian R. A. Buchanan explores the history of the British engineering profession, with work on early civil engineers who sought the status of gentlemen (1983), institutional developments (1985a), the development of scientific engineering (1985b), engineers' roles in the colonial empire (1986), engineers and government (1988), and, most recently, a comprehensive history (1989). In the same spirit, W. J. Reader (1987) and Judy Slinn (1989) offer histories of professional institutions. Sociologists Ian Glover and Michael Kelly (1987) trace how engineering has developed as an "occupation" in the context of the "professional ideal." As summarized by Chris Smith (1991), this project is part of a collective effort by "British managerialists" to revitalize the British economy by repositioning engineers at the center of the manufacturing enterprise. Attempting to learn from abroad by identifying "the best practice" in other countries, this movement seeks to reform British management along German lines, including empowering engineers (Child et al., 1983; Hutton & Lawrence, 1981; K. McCormick, 1988).

A parallel body of work explores the trials and tribulations of British technical education in the context of employer scorn and state disinterest. For example, numerous works attribute Britain's economic decline, in part, to its overemphasis on craft training for engineers (Ahlstrom, 1982; Albu, 1980; Barnett, 1986; Locke, 1984; Wiener, 1985). Some justify the emphasis on craft training (e.g., Robertson, 1981). In a pair of recent empirical studies, Colin Divall (1990, 1991) argues that corporate firms significantly influenced both the development of engineering education as an elite entry into professional engineering and the changing curricular balance between engineering science and design (see also K. McCormick, 1989).

In the British case, the work on class runs in parallel and is constituted by a conflict between Weberian and Marxian approaches. On the Weberian side, Peter Whalley has produced a sustained body of work whose constructivist orientation links it to recent social studies of science and technology and has made him a strong advocate of cross-national comparison. Initially arguing more generally for the need to consider the labor market positions of engineers as key contributors to and components of their class positions (Whalley, 1984, 1986; Whalley & Crawford, 1984), Whalley (1986) maintains in an extended treatise that British engineers fall into a more general cross-national class of "trusted workers." Continuing that occupations are "socially constructed achievements" (Whalley, 1987, p. 3), he finds cross-national comparison a necessary strategy for identifying the practical distinctions that each tradition devises to define the boundaries around and between trusted workers, such as between jobs and careers, works and staff, and exempt and nonexempt. Whalley's constructivist approach also argues for extending the analysis of technical workers into the political domain, because every boundary drawn must be seen not as a "technical necessity" but as a "political achievement" (Whalley, 1991, p. 210).

On the Marxian side, Chris Smith (1991, p. 457) critiques market-based accounts of class as "condition-based" descriptions, which could easily be examining surface labels or attributes, that miss the "economic conflict between staff and management." In an extended account of British technical labor drawing on fieldwork at British Aerospace, Smith (1987) maintains that national differences in "political expressions" of class identities does not mean that class has no "global voice" (see also Meiksins & Smith, 1991, in press).

Both France and Germany have developed highly stratified systems of technical workers that, by closely linking divisions among educational institutions to divisions among employers, repeatedly raise the question of class. At the same time, the very diversities in hierarchical organization that these national traditions have produced expand considerations of class formation well past labor market activity and labor/capital opposition. A significant difference between the two is that, while French engineers have consistently placed highest value on theoretical work that derives analyses from first principles, German engineers have modified the French model by integrating and valuing practical training and knowledge alongside engineering science.

Much research on French engineering examines the evolution and organization of institutions of higher education. Terry Shinn (1980a, 1980b, 1980c, 1984; Shinn & Paul, 1981-1982) analyzes in detail the hierarchical structure of the French engineering community, emphasizing the scientific prac-

tices of the highest level institutions, especially the Ecole Polytechnique. John Hubbel Weiss (1982) explores the class origins of nineteenth-century students at a second-level institution (Kranakis, 1989, pp. 9-10), the Ecole Centrale des Arts et Manufacturers. Charles Day (1978, 1987) directs his attention below both levels in exploring the development of the *ecoles d'arts et metiers*. Finally, in a comparative study of engineering practice in France and the United States, Eda Kranakis (1989) shows how the scientific orientation of the top strata shaped interactions among all three.

The occupational analogue of this educational hierarchy is the legally sanctioned hierarchy of *cadres*, a social category that emerged during the 1930s to distinguish grades of technical managers. In contrast with the United States and Britain, graduates of French engineering institutions generally expect to take their place within management, even valuing their training in abstract math and science primarily for managerial purposes. Luc Boltanski (1987) applies Bourdieu's theoretical perspective in accounting for the development of this new category, showing how the meanings that various classes attribute to it have varied over time, such that giving it any particular definition becomes "in itself a political act" (p. 181). Cecil Smith (1990, p. 659) "demonstrates the continuity" that public engineering and planning have maintained from the eighteenth century to the twentieth century as the highest prestige occupation for elite engineers. Finally, Stephen Crawford's (1989, 1991) accounts of contemporary engineers in low-tech and high-tech companies argue that the *cadre* system plays a more important role in shaping the class experiences of engineers than does the "logic of industrialism" (Crawford, 1991, p. 190).

In parallel fashion, research on German engineers traces connections between the establishment and growth of a network of educational institutions and the structure of German industry. Karl-Heinz Manegold (1978) describes how a German academic elite consolidated itself in the mid-nineteenth century, although the form of technical science that developed was not understood as applied science, as was the case in France. Also, in an extended history of German engineers, Kees Gispén (1988, 1990) traces the class-based tensions between academics and industrial employers.

Starting points for studies of engineering in other countries include Earl Kinmoth (1986), M. Kumazawa and Jomoko Yamada (1989), and Kevin McCormick (1992) on Japan; Cornelis Disco (1990) on the Netherlands; Rolf Torstendahl (1982a, 1982b, 1985) and Boel Berner (1992) on Sweden; Kendall Bailes (1978) on the Soviet Union; Anna Guagnini (1988) and Anna Barozzi and Vittoria Toschi (1989) on Italy; Knut Sorensen and Anne-Jorunn Berg (1987) and Carol Heimer (1984) on Norway; M. D. Kennedy (1987) on Poland; and Rodney Millard (1988) on Canada.

GENDER STUDIES

In every country where engineering has established significant representation in the workforce, the proportion of women engineers has been exceedingly small. Authors discussed in this section argue uniformly that the content of engineering education and practice conveys and reinforces masculine values, yet such is rarely mentioned in other contexts. Arguably, the established traditions of engineering studies outlined above have tended to reproduce the gender content of both engineers and engineering. In parallel with the shift from profession to class in studies of technical workers, gender studies over the past decade have undergone a shift from purely functionalist to power-based perspectives. Further developments in gender studies are critically important to the future of engineering studies because these force awareness of and attention to forms of stratification and hierarchy within engineering that both extend beyond the dimensions of class and have clear knowledge content.

Existing data about women in the "engineering pipelines" of the world show that the proportion of women engineers entering the workforce over the past 5 to 10 years has either held steady at a low value or actually declined (E. Jamison, 1985; National Science Board, 1989; U.S. Bureau of the Census, 1988; Way & Jamison, 1986). In the United States, demographic data indicate that the traditional pool from which future engineers are recruited (i.e., 18-year-old white males) is shrinking. As a result, recruiters are increasingly seeking women and minorities for engineering to fill national needs, but, regardless of these efforts, women still remain underrepresented in engineering, where only 1 in 25 engineers is a woman (Baum, 1990). When compared with science fields, engineering has the lowest representation of women (e.g., 3.1% in engineering and 4.7% in physics and astronomy) (National Science Foundation, 1991a). Questioning current recruitment strategies, Stephen Brush (1991) says that

we should consider the possibility that the young women who "leak out of the science and engineering pipeline" are behaving more intelligently than those who want to recruit them but refuse to provide adequate incentives. . . . The pipeline metaphor in itself is a clue to the problem: It suggests a factory-management attitude that treats people as raw material to be made into products, without regard for their own wishes or well-being. (p. 416)

Prior to 1985, virtually all research on women in engineering adopted what Judith McIlwee and J. Gregg Robinson (1992, pp. 13-18) call the "gender role perspective." Related to the labor market approach to class outlined above, such studies explained the nonparticipation of women in engineering

as a product of their socialization as women. In some of the earliest studies, Alice Rossi (1965, p. 1201, 1972) describes women as preferring fields in which they can work "with people rather than things." Also, Carolyn Perrucci (1970; Hass & Perrucci, 1984), one of the first scholars to investigate the experiences of women in engineering, emphasizes the significance of family responsibilities in women's lives and the roles of socioeconomic background and education in shaping occupational choices. Finally, Mildred Dresselhaus (1984) argues that women faculty members in engineering institutions are necessarily political actors who have "extracurricular" responsibilities to encourage women students to form networks with women colleagues and to influence developments in national policies.

A correlate of this interest in the socialization of women engineers is that survey research has tended to focus on education rather than employment (e.g., Ott & Reese, 1975). Numerous studies show that women tend to enter engineering programs with higher grades and test scores than men (Gardner, 1976; Greenfield, Holloway, & Remus, 1982; Jagacinski & LeBold, 1981; Ott, 1978a, 1978b). Surveys also indicate that women are more likely than men to enter engineering if some family members, especially their fathers, were engineers (Auster, 1981; McIlwee & Robinson, 1992). To the extent that such work studies practicing women engineers, the focus has been on the significant salary gap between men and women (McAfee, 1974; Rossi, 1972; Vetter, 1981). See, however, Carolyn Jagacinski's (1987a, 1987b) recent work showing that women engineers are also less likely to be married and to have children than men.

Research on the history of women engineers has emphasized the heroic characteristics of such women. E. Rubenstein (1973) characterizes her early overview of women electrical engineers as "profiles in persistence." Martha Trescott (1979b, 1982, 1984) also emphasizes individual persistence in reporting the results of a survey of 500 practicing women engineers and tape-recorded interviews with nearly 50 older women engineers "who have made significant contributions to the theory, design, management, or education, or to the history of the Society for Women Engineers" (Trescott, 1984, p. 181). Examining in detail the life of Lillian M. Gilbreth, the mother in *Cheaper by the Dozen* and perhaps "the most well-known woman engineer in history," Trescott (1984, p. 192) also argues that women engineers tend to adopt a "holistic" approach to engineering problem solving.

The major impetus for integrating power-based perspectives into studies of gender in engineering has come in the work of Sally Hacker. Dorothy Smith and Susan Turner edited a collection of her papers on gender and technology, introducing each chapter with transcriptions from interviews that Smith did with Hacker prior to her death in 1988. This editorial approach systematically displays Hacker's central goal of constructing a "people's

sociology" (Hacker, 1990, p. 2) that uses available theories and methods as tools to empower dominated or exploited people by critically examining how macrosocial processes affect them, including the organization and policies of government, corporations, and universities. Following a research method she calls "doing it the hard way," which means getting in and "being with people" to "know what it feels like," Hacker (1990, pp. 105-110, 157) draws on a year of fieldwork at MIT followed by engineering course work at Oregon State University to outline the "masculinist bases" of "engineering culture."

Hacker's (1990) central claim about engineering is that the "culture of engineering" in universities and in the workplace constitutes and reproduces "patriarchal" systems, that is, "sex-stratified systems in which men are dominant" (p. 50). For example, she explains and criticizes the emphasis that engineering education places on testing in mathematics as "embedded in a very masculine-shaped professional organization of knowledge and evaluation" (p. 109). She uses jokes told by engineering professors to argue that "persistent mind-body dualism" (p. 123) structures hierarchies in universities and the workplace to the detriment of women. Furthermore, she maintains that engineering training channels the passions of engineers, particularly erotic energies, into their experiences of technology (pp. 210-212; see also Hacker, 1989), joining this emotional experience with the emphasis on mathematics to produce engineering managers with a " 'blind spot' about social structure" (p. 127). Interpreting capitalist domination as a form of "patriarchy," Hacker (1990, pp. 177-179) adopts the deskilling hypothesis to argue that, like other workers, engineers are being disempowered by automation technologies, especially by computer-aided design and computer-aided manufacturing.

In a sensitive and systematic challenge to Hacker's analysis of patriarchy in engineering, Judith McIlwee and J. Gregg Robinson weave quantitative data from a sample of 407 working engineers with qualitative data from 82 in-depth interviews to assess the experiences of women in engineering from the precollege years to the workplace and beyond. Framing their arguments in a "conflict-structural" perspective, they link considerations of gender socialization to an understanding of universities, corporations, and families as structures of power relations. McIlwee and Robinson see Hacker's emphasis on abstract mathematics as but one variant of engineering culture that is found in the university that misses the cultural emphases engineers place on tinkering with technology, organizational power, and male presentational style in the workplace (McIlwee & Robinson, 1992, pp. 26-33). This leads to the interesting conclusion that women engineers tend to fare worse in organizations in which engineers are more powerful, such as computer and other high-tech firms, and better in large industrial bureaucracies, such as aerospace firms, within which affirmative action policies have become

established practice. Along the way, McIlwee and Robinson offer many insights into how women "drift" into engineering careers, how the "interactional structure" of college presents barriers that women overcome with strong performances in math and theory, and how women encounter new sets of barriers in the workplace built around the valuation of tinkering and the appropriate presentation of self.

STUDIES BY ENGINEERS

By far the greatest volume of literature interpreting the experiences of engineers is produced, of course, by engineers. Such writings can be of use to other researchers in engineering studies in at least three ways. First, engineering committees and organizations regularly collect and publish massive amounts of quantitative data about engineers. Second, the writings of engineers typically defend engineers' points of view, thus providing a useful source of data about how engineers understand what they do. Third, numerous engineers have made the effort both to address nonengineering audiences and to get beyond self-justification to offer interpretive accounts that take their place alongside those of other analysts. Such accounts tend to focus on engineering ethics, the appropriate content and duration of education, and relations between engineering science and engineering practice.

Committee and organizational studies by engineers are generally organized along national lines. As a starting point, we recommend you identify by searching references at least one such body in the country you wish to study and use it to locate others. UNESCO publishes many useful international studies, such as reviews of continuing engineering education (Ovensen, 1980), engineering manpower (Van den Berghe, 1986), the environment in engineering education (Brancher, 1980), and engineering and endogenous technology (UNESCO, 1988).

In the United States, which we have reviewed in some detail, the rise of nationalist concern during the 1980s about "economic competitiveness" has elevated engineering to the status of a national problem. Numerous studies document American problems with productivity and point to developments in engineering education and engineering-oriented developments in process technologies as the pathway to solutions.

The National Academy of Engineering (NAE), in cooperation with the National Research Council (NRC), and the National Academy of Sciences (NAS) has taken the lead. A key starting point is a comprehensive NRC assessment, "Engineering Education and Practice in the United States," published in nine slim volumes on such topics as engineering technology education (NRC, 1985a), engineering graduate education and research (NRC, 1985b),

engineering in society (NRC, 1985c), support organizations for the engineering community (NRC, 1985d), engineering employment characteristics (NRC, 1985e), continuing education of engineers (NRC, 1985f), engineering education and practice (NRC, 1985g), engineering undergraduate education (NRC, 1986a), and engineering infrastructure diagramming and modeling (NRC, 1986b). The NAS has published reports on the underrepresentation and career differentials of women and minorities in science and engineering (Dix, 1987a, 1987b) and engineering personnel needs for the 1990s (NAS, 1988). The NAE reports have dealt with education and employment of engineers (NAE, 1989) and engineering and competitiveness (NAE, 1983, 1985, 1986, 1987a, 1987b). The National Science Foundation also publishes a biennial report on the status of women and minorities in science and engineering (NSF, 1990).

Other useful sources include professional engineering societies, universities, and ad hoc organizations. For example, *Manpower Comments*, a monthly bulletin published by the Commission of Professionals in Science and Technology, provides information on supply and demand, salaries, representation of women and minorities, and education in science and engineering.

For writings by engineers that present and justify engineers' points of view, the best source of data is paging through the "comments" and "opinions" sections of professional journals and magazines as well as the semipopular technical publications, such as *Technology Review* and *Prism* (formerly *Engineering Education*).

Among those engineers who have presented interpretations of engineers in the context of other such interpretations, Samuel Florman has produced the most extended body of work. A civil engineer, co-owner of a construction firm in Manhattan, and holder of a master's degree in English literature from Columbia University, Florman has published several books (1968, 1976, 1981, 1987) and writes a monthly column for *Technology Review*. Although sometimes interpreted by critics as a literary apologist for engineers, Florman is diligent in formulating accounts on a wide variety of topics, especially liberal education for engineers, that directly engage and frequently challenge alternative accounts of engineers.

Henry Petroski (1985) makes an important contribution to demystifying engineering design by linking features of everyday life to the practices of engineers. By describing the multiple meanings that the term *failure* has for engineers, Petroski builds a framework for evaluating future changes in design practices, such as increasing reliance upon computer software. Peter Booker (1979) offers a detailed and insightful history of the genesis of engineering drawing concepts. His historical overview actually provides a thorough survey of contemporary concepts for it is a series of episodes whose sequence documents the sequential appearance of these concepts. Richard

Meehan (1981) presents an autobiographical account that systematically identifies links between nonengineering society and the content of engineers' knowledge, arguing, for example, that the "big questions" that ground and that threaten the engineers' authority "are the freshman questions, not the graduate school questions" (p. 43). Arthur Squires (1986) draws on his own experiences to document the inadequacies of "governmental management of technological change" in the United States and calls for managers to identify and promote "maestros of technology" from among the ranks of engineers and other technological "apprentices." Finally, Dan Pletta (1984) offers a call for an independent sense of "professionalism" in engineering.

For other work on engineering education, see Grayson's (1977) brief history of engineering education, Wakeland's (1990) proposal for internationalizing engineering education, and Abbott's (1990) account of the effect of American culture on engineering education. For work on popular attitudes toward engineers, see Vaughn (1990), A. M. Weinberg (1989-1990), Critchley (1988), and K. Strauss (1988).

KNOWLEDGE AND POWER IN ENGINEERING

Although research agendas in each of these four areas—engineering knowledge, engineering as technical work, gender studies, and studies by engineers—is reasonably well developed, the work in each area could benefit from enhanced critical dialogues. We believe that much could be gained if each researcher asked seriously: How might insights generated in other areas contribute to my accounts, and how might insights in my work contribute to accounts in other areas? In fact, judging from the array of studies we have reviewed, an implicit dialogue has already been emerging over at least one conceptual question that promises to position a great deal of work in the next generation of engineering studies: How do knowledge and power operate and interrelate in the activities of engineers? This conceptual question pushes each of the areas into new directions.

Much of the research on knowledge in engineering has been demarcationist in tenor and objective. We suggest that demarcationist approaches shift their orientation slightly, but significantly, from documenting the distinctiveness of engineering knowledge to investigating demarcationism as an engineering practice. The published work clearly establishes the empirical worthiness of exploring the contents of engineering knowledge; such is breaking entirely new ground. However, as a conceptual strategy, demarcationism has not held up well to critical examination elsewhere. Philosophers of science, for example, have found no characteristics that appear to be essential to knowledge in the natural and physical sciences. Accordingly, we

believe that essentialist claims about the engineering sciences are likely to be of lesser lasting significance than the empirical value of documenting in detail the conceptual contents of engineering knowledge. By shifting strategies from defending logical relations within engineering knowledge to exploring the strategies through which engineers construct, maintain, and transform these relations, studies of engineering science could better account for the precise features of engineering theories and link with the constructivist and actor-network accounts of engineering design.

Such reorientation generates new research questions. For example, David Channell (1982) reports that Rankine purposely conceptualized engineering science in a way that did not look like applied science or challenge the apprenticeship system. This interesting insight could be elaborated in an account of how Rankine's strategies for demarcating engineering science incorporated his social strategies for legitimizing such activity in the scientific and engineering communities and established him as an authoritative figure. In other words, examining the conceptual strategies of designers as part of a broader set of social strategies also links accounts of engineering epistemology to biography, social history, and social studies. Some of the empirical questions that emerge include these: How do engineers develop, maintain, and assess boundaries among engineering disciplines (see Donovan, 1986)? How has the evolving legitimacy of engineering science been linked to the evolving legitimacy of engineering education? How do engineers in both universities and industry vary in valuing the distinction between engineering science and engineering design?

Almost all studies of engineering as technical work, as Peter Whalley (1991, p. 197) perceptively points out, view engineering knowledge as a defining feature of the professional or class status of engineers, but none of this work examines the knowledge content of engineering in a sustained way. If the class-based powers of engineers are linked to the knowledge contents of their engineering, then there is merit in shifting from taking for granted the knowledge-based authorities of engineers and exploring how knowledge strategies are related to class strategies. Empirical questions that emerge include these: How are status differences between design and manufacturing engineers linked to the contents of their knowledge? How are disciplinary differences related to the different class experiences of engineers, as indicated by the historical shift of intellectual hegemony from civil to mechanical to chemical to electrical engineering? What makes engineering work satisfying or not? What are the class implications of engineers doing satisfying or unsatisfying work? Following the call of James Watson and Peter Meiksins (1991), we support "shift[ing] the focus of research away from issues such as professional autonomy toward the nature of engineering work itself" (p. 165).

Perhaps the greatest contribution of research on gender in engineering studies is that it raises issues that clearly have both knowledge and power content, although the emphasis has been more on power than knowledge. While Sally Hacker points to the "masculinist bases" of testing in mathematics, for example, her work does not extend to consider the contents of the mathematical knowledge demanded of engineers, as is outlined in the research on engineering science and engineering design. Further questions that arise include these: What knowledge and power considerations shape the participation of women in industrial or mechanical engineering and their avoidance of electrical engineering? Despite the evident capabilities of women engineering students in mathematics, are those women who leave engineering expressing an unwillingness to accept professional identities built on "engineering problem solving"? What do the differing positions of men and women engineers in industry tell us about hierarchies of valued knowledge in the workplace?

Gender studies also force attention to two additional subjects of inquiry not engaged in the other areas: forms of hierarchy and stratification not based entirely in class, such as race, age, and ethnicity, and full accounting for the emotional dimensions of engineers' experiences (see also Sinclair, 1986). Research questions proliferate. Since 1983, more than 50% of the Ph.D.s awarded in engineering in the United States have been awarded to non-American-born students. The engineering faculties of universities in many countries have majority memberships of noncitizens. As multinational corporations gain in cross-national power, the ethnic makeup of their engineering staffs is changing significantly. What are the implications of increasing racial, ethnic, and cultural diversity in various arenas of engineering activity? Regarding the emotional status of engineers, how is it that engineers routinely feel powerless themselves but are viewed as highly empowered by outsiders? How is the "boring nerd" image of engineers constructed and maintained? Are engineers' pleasures in tinkering with mechanical technologies being replaced by computer hacking? What might be the gender implications of such a shift?

The engineers who represent the activities and practices of engineers to audiences of nonengineers could make a unique contribution to exploring questions of knowledge and power. Rather than presenting engineering communities as integrated wholes to explain engineering to outsiders, such work could provide insight into power relations within such communities. For example, how do new theories and methods, such as the rise of interest in numerical methods, gain acceptance among engineering researchers? What are the diverse considerations that shape the development of engineering curricula and the practices of instruction? What are the steps through which engineering students gain membership in engineering communities?

How do technical standards function in everyday engineering practices? What are the roles and implications of engineers participating in setting such standards?

Finally, we believe that the rise of cross-national comparative research on engineering introduces the potential for many new insights into the immense diversity of knowledge/power relations in engineering. Cross-national comparisons of engineers illustrate not only the commonality of capital-labor tensions in capitalist industrial systems (e.g., Smith, 1991) but also the contrasts among engineers' experiences within and between different systems. Given that we are all writing during a historical period in which the political economy of the world no longer appears to consist of a dualistic struggle between monolithic capitalist and communist systems, it seems likely that diversities among and within capitalist systems will become the object of greater scholarly and political attention. Both the nature of class conflicts and the very concept of class are nationally, even locally, variable. Research on the variable locations and experiences of engineers in both knowledge and power terms positions engineering studies at the center of such broader concerns. Overall, establishing enhanced dialogues within engineering studies about the interrelations of knowledge and power in engineering promises to take us a long way toward understanding the nature and organization of the diverse interrelations among science, technology, and capitalism.