DOCUMENT RESUME

ED 314 642 CE 054 024

AUTHOR	Raizen, Senta A.
TITLE	Reforming Education for Work: A Cognitive Science Perspective.
INSTITUTION	National Center for Research in Vocational Education, Berkeley, CA.
SPONS AGENCY	Office of Vocational and Adult Education (ED), Washington, DC.
PUB DATE	Dec 89
GRANT	V051A80004-88A
NOTE	81p.
AVAILABLE FROM	National Center for Research in Vocational Education Materials Distribution Service, Western Illinois University, 46 Horrabin Hall, Macomb, IL 61455 (Order No. MDS-024: $6.25).
PUB TYPE	Information Analyses (070)
EDRS PRICE	MF01 Plus Postage. PC Not Available from EDRS.
DESCRIPTORS	Apprenticeships; Basic Skills; Cognitive Development; *Educational Improvement; *Educational Needs; *Education Work Relationship; Entry Workers; *Experiential Learning; *Learning Processes; Postsecondary Education; Problem Solving; Research Reports; School Business Relationship; School Effectiveness; Secondary Education; *Vocational Education
IDENTIFIERS	Workplace Literacy

ABSTRACT

Over the past decade, research by cognitive scientists has been building a clearer understanding of how people learn in school and out. A review of the various streams of cognitive research has implications for vocational education. Research has determined characteristics of effective workers and how people become effective workers. Some highlights of this research are that (1) the usual teaching of skill hierarchies is seldom effective in educating and training for work; (2) people build workplace expertise through the opportunity to participate, under the training of experts, in physical and intellectual tasks specific to a particular work setting; (3) the abstract thinking skills required in many technical jobs today are learned effectively through a combination of practice and explicit teaching in a meaningful context; and (4) impediments to providing the opportunity to participate in meaningful work experiences include the increasing emphasis on school-based, formal education, the insistence on sequential learning of skill hierarchies and general reasoning skills without application to practice, and the increasing complexity of jobs, which makes craft-style apprenticeship ineffective. To improve education for work, vocational education needs to integrate learning of basic skills with learning of specific work setting skills, to provide education for work in replications of work situations, and to recognize the relationship between healthy families, schools that educate, and productive workplaces. Over 100 references are cited and a list of 20 researchers consulted is appended. (KC)

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Supported by
the Office of Vocational and Adult Education,
U.S. Department of Education

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National Center for Research in Vocational Education
Materials Distribution Service
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Macomb, IL 61455

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Supported by
The Office of Vocational and Adult Education,
U.S. Department of Education

December, 1989

MDS-024

FUNDING INFORMATION

Project Title:	National Center for Research in Vocational Education
Grant Number:	V051A80004-88A
Act under which Funds Administered:	Carl D. Perkins Vocational Education Act P. L. 98-524
Source of Grant:	Office of Vocational and Adult Education U.S. Department of Education Washington, D.C. 20202
Grantee:	The Regents of the University of California National Center for Research in Vocational Education 1995 University Avenue, Suite 375 Berkeley, CA 94704
Director:	Charles S. Benson
Disclaimer:	This publication was prepared pursuant to a grant with the Office of Vocational and Adult Education, U.S. Department of Education. Grantees undertaking such projects under government sponsorship are encouraged to express freely their judgement in professional and technical matters. Points of view of opinions do not, therefore, necessarily represent official U.S. Department of Education position or policy.
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REFORMING EDUCATION FOR WORK: A COGNITIVE SCIENCE PERSPECTIVE

INTRODUCTION

Over the past decade, research by cognitive scientists has been building toward a clearer understanding of how people learn in school and out. This paper is an attempt to bring together the various streams of cognitive research and explore implications for vocational education. In particular, the following questions are addressed: How is the world of work changing, and how do these changes affect competencies needed by workers? What is known about the differences between effective performance and less skilled performance, and how do individuals acquire expertise in a job? What are the relationships between what are usually considered basic or general skills (e.g., literacy, numeracy, reasoning skills, and the ability to solve problems), knowledge in a specific domain, and competency in a related job or profession? How do people actually solve problems on the job, and what are the skills and competencies that characterize good work performance? How effectively do people transfer their formal school-based instruction to situations outside school and apply it on the job? What is the role of an apprenticeship, and what are its modern equivalents?

Given the evidence about acquisition and the effective use of job knowledge to produce competent performance, how should vocational education be formulated to meet the needs of individuals preparing for work? Should most of it be offered in formal school settings and be integrated with traditional school subjects? Should it be offered in work settings and integrated with on-the-job education? What would work arrangements have to be to facilitate an effective equivalent of apprenticeship training? What changes need to be made in its curricular content; in its pedagogic strategies; and in the current arrangements for vocational education? This paper is intended to contribute to the current debate about the nature of vocational education and the reforms needed by presenting, in summary form, relevant evidence from recent cognitive science research about how people learn to be competent in their work.

BACKGROUND

Recent Concerns with Vocational Education

Continuing Criticisms

Vocational education has been reexamined and reformulated almost from its inception in 1917. The frequency of evaluation and recommendations for change seem to have accelerated over the last several decades, with two comprehensive investigations mandated by Congress within a decade (National Institute of Education, 1979, and the current National Assessment of Vocational Education). During the 1960s and 1970s, statutory change in federal employment and training and the related education programs became an annual event (Swanson, 1979). The 1968 legislation was particularly significant, making federal funding available for categorical programs aimed at target populations and building in data analysis and evaluation to check on the use of the funds (Bogetich & Lammers, 1979). This focus on target populations was quite in line with the general policy environment of the times which saw education as a basic strategy for lifting people out of poverty. Despite continuing criticism, however, the growth of vocational education—no doubt responding to the growth of the school-age population—nearly kept pace with the growth of the education sector itself in both funding and enrollment (National Assessment of Vocational Education, 1989). The 1980s have been characterized by a series of vocational education assessments performed one after the other (National Institute of Education, 1980, 1981; National Commission for Employment Policy, 1981, 1982; Gardner, Campbell, & Seitz, 1982; Sherman, 1983; and more than twenty separate studies done for the National Assessment of Vocational Education mandated by Congress as part of the Carl D. Perkins Vocational Education Act of 1984, PL 98-524, which reauthorized vocational education five years ago). Influenced by the current policy environment which stresses accountability, the emphasis has been on enrollment patterns, the outcomes of vocational education for various population subgroups, and the distribution of funding and services (Grasso & Shea, 1979).

Each reexamination and legislative change has been in response to criticisms which were partly inherent in the original conception and partly generated by new social conditions such as the Depression of the 1930s, the changing industrial conditions and labor market needs following World War II, the concern in the 1960s with assisting individuals traditionally unsuccessful in the labor market, and the attempt in the 1970s to reintegrate academic and vocational education through career education. As in most debates in education, discussions of program quality and effectiveness have masked fundamental disagreements and shifts in goals. For example, the original Smith-Hughes Act of 1917 envisaged a system of education distinct from academic education which would prepare youths—hitherto absorbed by the need for unskilled labor—for the newly emerging demands for more and more skilled labor. Yet, even then, there was also the less overt goal of keeping students in school longer by integrating their academic education with vocational preparation which, incidentally, kept them out of the labor market longer (Walsh, 1979). Within two decades, the program came under heavy criticism for creating a dual education system, for its narrowness of training, and for its lack of economic payoff (Russell & Associates, 1938). As Grubb (1979) observes, while the report had little impact because of the skilled labor shortages created by World War II, it set a pattern that subsequent reports followed. In short, vocational education has at various times been held responsible for—and criticized for not succeeding in—resolving issues of unemployment involving unskilled and underskilled young people, making schools relevant to young people not interested in higher education, integrating various population subgroups into school and work, and expanding educational opportunity (and thereby reducing the dropout problem) by offering an educationally and economically valuable alternative to traditional academic education.

Alternative Training Systems

Parallel to concerns and legislation dealing with vocational education and the education system in general, the 1960s saw the creation of a separate system of employment and training administered through the U.S. Department of Labor and its state counterparts. The system evolved from the Manpower Development and Training Act (MDTA), the Economic Opportunity Act, and the Emergency Employment Act into the Comprehensive Employment and Training Act (CETA) in the 1970s, which set up a whole parallel training system outside the schools, and the Youth Employment and Demonstration Programs Act (YEDPA), which was designed to yield definitive information on what sorts of programs were most effective in helping youths obtain and hold on to jobs productive both for them and for the economy. The current version, the Job Training Partnership Act (JTPA), stresses the involvement of the private sector. The creation of these programs rested on several assumptions implicitly critical of vocational education and of education in general: (1) that schools were not philosophically equipped to deal with either the needs of hard-to-place youth or the needs of the labor market; (2) that school people lacked the appropriate experience and know-how; and (3) that labor, business, industry, and community organizations were more appropriate sponsors, not only of specific job training, but also for providing the more general kind of education needed to get, hold, and advance in a job. However, as Vaughan and Berryman (1989) point out, the training programs funded under the successive legislations have provided entry level skills designed to enable individuals to get jobs at the bottom rung of the ladder, jobs that provide little opportunity for advancement, or jobs that are the most likely to be abolished through automation.

Reasons for the Current Review

In preparation for the reauthorization of the Perkins Act, there is presently another flurry of vocational education studies being done, with the most important one being the National Assessment of Vocational Education. At the same time that this current reexamination program is going on, the U.S. Department of Education is also funding a National Center on Education and Employment and a National Center for Research in Vocational Education which were set up to consider and research salient long-range issues.

Why the continued concern with vocational education? Is there anything new about this topic that has not already been fully explored by the many investigations in the past? It is true that some of the current questions about vocational education are reformulations of past criticisms such as the tendency to segregate poor and minority youths into a track that offers diminished access to high status, high pay careers—a violation of equal educational opportunity goals; the misfit between the skills training offered in the programs and the needs of a rapidly changing economy; the narrowness of the education and the lack of economic payoff for most of it; and the failure of the programs to address the dropout problem or the problems of the unemployment and the unemployability of a sizable segment of the youth population, largely minority and poor.

There are, however, several factors affecting vocational education today that, if not all new, are qualitatively different from earlier social and economic changes:

- The U.S. economy's need for a technologically highly sophisticated workforce because of the development of a global economy and the advance of communication technologies (an argument disputed by some analysts);
- The changing composition of the labor force, which will be made up of increasing numbers of individuals for whom the current programs have not been successful;

- The current wave of educational reform and its effects on enrollments in vocational education programs; and
- New research findings from cognitive science on how people learn in and out of school.

This paper is mainly concerned with the application of cognitive science research to vocational and other educational programs intended to help people participate successfully in the world of work. First, however, it is necessary to take a brief look at the changes in that world and in the world of education.

The Changing Needs of the Economy

Traditionally, vocational education, manpower programs, and such related programs as career education and transition from school to work have had as their specific mission the preparation of young people—and, more recently, adults facing job dislocation—for the labor market. Generally, the programs were intended to provide students with broad literacy skills, specific technical training, and attitudes that would allow them to obtain and maintain themselves in productive jobs. In practice, however, there has almost from the beginning been a tension between providing specific occupational skills for jobs deemed in short supply and providing more general skills that would allow greater occupational choice. (See Carnoy & Levin, 1985, pp. 92-97, for a discussion of the origins of the occupational versus general skills debate.)

This issue is longstanding, revolving as it does around the ability of students to find the specific jobs for which they have been trained, largely a function of the youth labor markets. However, the tension between training for specific jobs and the development of more general skills has become increasingly evident as the U.S. economy has become more tightly bound to the world economy because of advances in communications, and as automation has radically affected the production of goods and services. Economists studying consequent changes in the workplace (Bailey, 1988; Noyelle, 1989) have observed a shift from mass production to flexible production in both the manufacturing and service industries. They argue that this shift requires workers with a much wider range of competencies and skills than before. Hoachlander, Kaufman, & Wilen (1989) argue that "[T]his general trend is projected to continue into the near future; from 1986 to 2000 the fastest-growing jobs will be those currently filled by the best-educated portion of the labor force" (p. 18).

Further accelerating this trend is the continuing growth of the knowledge base that undergirds the economy. In several of the engineering fields, for example, the half-life of an individual's technical training is approximately ten years, and support positions often are similarly affected.

The argument that the U.S. economy is undergoing a major transformation is by now a familiar one. This transformation, which is no less fundamental than the shift from an agricultural to an industrial economy a century ago, can be characterized as follows:

- The extension of human muscle power which ushered in the industrial age is being paralleled by the extension of human brain power through the artifacts of the information revolution—computers, automation, and telecommunications.
- Furthermore, these technologies have created such a rapid information exchange that the economies of countries and even continents are becoming ever more closely linked, creating one global economy. The United States is still taking its first halting steps toward recognizing that it now must compete in a world market rather than relying solely on domestic consumption as being the engine of U.S. productivity.

There are several consequences of these developments: (1) U.S. manufacturing is changing its character; (2) most new jobs will be in the service industries, some requiring high level skills, others requiring very little training; (3) the pace of change can be expected to increase as technological advances increase, making all but the broadest sort of forecasts about labor market needs increasingly tenuous and leading to obsolescence of vocational education programs designed around tightly defined skills; and (4) these uncertainties have led many analysts to argue that programs to ready individuals for work should emphasize generalizable skills rather than training for a specific occupation.

Changes in Manufacturing

The United States is likely to be able to compete with manufacturing industries abroad only under conditions where its highly educated and highly paid labor force can be used to best advantage. This means that large batch manufacturing which turns out mass quantities of the identical product is being replaced by manufacturing which is geared to small quantities of custom designed orders and fast delivery.

Bailey (1988) has described the changes in the textile industry as it underwent this sort of restructuring. While the modernization drive was well under way in this industry before the advent of new technology, programmable microelectronics made possible more rapid shifts to flexible production. The consequences for skill requirements are still under debate. According to Bailey, while lower level workers (e.g., machine operators) may need even less sophisticated skills than before, most other workers will require greater skills—as much because of the reorganization of the production process as because of the introduction of new technology. The jobs of even the lower level production workers are more demanding, he argues, because they need to develop a more abstract understanding of their tasks and how these tasks relate to the whole production and marketing processes of the firm. Further, he finds that, "As work moves from a mass production focus to one that emphasizes flexibility, group interaction and social skills become more important for skilled and less skilled workers alike. We need to strengthen students' abilities to work cooperatively as part of a group" (p. 52).

Growth in the Service Industries

As manufacturing becomes customized, more highly automated, or moves offshore (even when American-owned) to take advantage of cheap labor, the service industries will continue to grow. According to one estimate (Sherman, 1983), approximately eighty-four percent of all new jobs between 1940 and 1980 were in the service sector, with the proportion of nonagricultural workers engaged in manufacturing falling from thirty-four percent in 1940 to twenty-two percent in 1980.

Banking, for example, is undergoing restructuring as computerization replaces routine hand processing of transactions and international markets are created for the services banks provide such as financing. Thus, in the banking industry, low level personnel have been replaced by better educated middle level personnel who work with automated systems and take on both lower level and higher level functions (Bailey & Noyelle, 1988).

Even a brief look at the service industry sector points up an important lesson: the service industries encompass very different kinds of occupations (Personick, 1987). Jobs in technology and information-based businesses will require sophisticated know-how and skills; those in food, janitorial, and over-the-counter sales will require little by way of specialized skills.

Changes in the Total Economy

Although debates about whether the economy is upskilling or downskilling continue to rage, historically the United States occupational structure shows a long term, steady upskilling.

The economy has been shedding lower skill and adding higher skill jobs throughout the twentieth century. For example, the 1900 decennial census showed that about thirty percent of the experienced labor force worked as agricultural or nonagricultural laborers; and ten percent worked in professional, technical, or managerial occupations. By 1980, these percentages had roughly reversed with six percent working as laborers and twenty-six percent working in the professional, technical, or managerial occupations (Berryman, 1989). By 1988, higher skill occupations accounted for thirty-seven percent of total jobs; lower skill occupations gave rise to sixty-three percent.[1] However, between 1976 and 1988 the higher skill jobs accounted for fifty-six percent of total job growth, and the lower skill jobs for forty-four percent of total job growth. In other words, during this twelve year period, higher skill jobs grew at rates greater than would be expected on the basis of even their 1988 share of total jobs (Bailey, 1989).

We see the same picture in the Bureau of Labor Statistics occupational projections for 1988-2000. The higher skill jobs are expected to account for fifty-five percent of total projected job growth for this time period, a share greater than their 1988 share of total jobs (thirty-seven percent) and resulting in a shift in the 2000 share of total jobs to forty percent.

These projected growth rates translate into an upward step in educational levels. When we use U.S. Census data to look at the educational distribution of the total 1988 labor force, we find that seventeen percent had not completed high school; 40.5% had completed high school only; 20.7% had completed one to three years of college, and 21.8% had four or more years of college. Using the educational distribution data for each occupation in 1988—that is, assuming that there will be no change in that distribution between 1988 and 2000—we can calculate the educational distribution of the net new jobs projected to be added to the labor force between 1988 and 2000. This distribution of the net new jobs by 2000—*not of the total labor force in 2000*—will be 13.2% non-high school graduates, thirty-five percent high school graduates, 22.1% with one to three years of college, and 29.7% with four or more years of college. Since the number of new jobs

[1] Bailey (1989) defines "higher skill occupations" as ones whose incumbents have an average level of education higher than the average for the total labor force. He defines "lower skill occupations" as ones whose incumbents have an average level of education lower than the average for the total labor force. Higher skill occupations thus include the professional specialty occupations; technicians and related support occupations; executive, administrative, and managerial occupations; and marketing and sales. Lower skill occupations include administrative support occupations (including clerical jobs); service occupations; precision production, craft, and repair occupations; agriculture, forestry, fishery, and related occupations; and operators, fabricators, and laborers.

expected to be added between 1988 and 2000 only represents fifteen percent of the 1988 total labor force, the upward shift in educational levels for the net new jobs will not substantially change the educational distribution of the total labor force in 2000. However, they will move it upward.

All that this data tells us is the occupational and educational direction of the labor force. It does not say that the economy does not have lower skill jobs. It does and will continue to do so. In fact, it is predicted that by 2000 sixty percent of the labor force will be made up of lower skill jobs, if we define "low skill" as an occupational category whose average educational level is below the average for the total labor force. This data also does not say that everyone needs a college degree in order to work: even by 2000 only about a quarter of the workforce is expected to have four or more years of college.

As important as changes in the occupational structure of the U. S. economy, if not more so, are changes *within* occupations. Bailey (1989) documents how the skill requirements of high skill jobs and of a substantial share of low skill jobs are blurring. These changes and their educational implications do not show up in the occupational numbers.

In sum, data on changes in the occupational structure, data on changes in the skill demands of many low skill jobs, and data on income tell us something very sobering. The better educated face a future of expanding opportunities and rising wages; the poorly educated face a future of contracting opportunities and poverty. For the individual young person, the choice is clear: invest in the education that lets him or her weather changes in labor markets, and take advantage of opportunities that would be reserved for the better educated.

Continued Rapid Changes

Another consequence of the information-age revolution is the ever increasing need to make continuing adaptations to a rapidly changing economic environment, thereby decreasing the ability to forecast with any degree of certainty the skills needed by the labor market. Since the lag time between establishing a need for specific skills fitting a particular occupation that exhibits shortages and the development of a program to respond to that need is considerable, there is always the danger that the program and its equipment will be outdated before it graduates any students. A recent example is the plethora of vocational training programs created a decade ago to teach low level computer programming just as these jobs were becoming obsolete. Another example at a higher skill level is the demand generated by the 1970s oil crisis for petroleum engineers which rapidly abated in the

1980s. Yet another example comes from the electronics industry. According to the U.S. Department of Labor (1987), this industry recorded a 3.4% drop in total employment between 1985 and 1986, representing a decline of 75,000 jobs; component companies saw a drop of 33,000 jobs (0.5% of their workforce); computer manufacturers lost 418,000 jobs (7.4%). As conditions in the labor market continue to change rapidly, questions about the usefulness of creating or attempting to create tight fits between vocational education programs and specific labor market needs become more and more insistent.

Skills Needed in the Workplace

The set of circumstances briefly described above has led many researchers in the field to argue that educational programs designed to enable individuals to obtain productive jobs and contribute to the economy need to concentrate on generalizable skills. The question then becomes, "What are these skills, and how do they differ from the basic skills that have traditionally been part of formal schooling?"

New skills or old? One difference is that current listings of skills needed in the changing work environment try to encompass dispositions and habits that would make individuals effective in almost any setting. For example, a recent list developed by Levin and Rumberger (1989) includes several cognitive competencies generally deemed to be goals of formal education such as communication, reasoning, problem solving, obtaining and using information, and the ability to continue learning. But they also list the following dispositions as needed in the workplace: the willingness to take initiative and perform independently; the ability to cooperate and work in groups; competence in planning and evaluating one's own work and the work of others; understanding how to work with persons from different backgrounds and cultures; and the ability to make decisions. A recent survey of Michigan employers (Roeber, Brown, & Stemmper, 1989) gave highest priority to personal management skills (e.g., self-control, honesty and integrity, pride in one's work, and respect for others), second priority to academic skills, and third priority to teamwork skills. The problem is that the concepts that give rise to dispositions and habits desired by employers are not well delineated. For example, what lies behind an individual's willingness to take initiative or the ability to plan? What is entailed in cooperation or decision making? How do you teach pride in one's work and respect for others? Until these concepts are reasonably well defined, it is difficult to envisage how the desired habits and dispositions might be taught effectively. The fact that many people do not succeed too well in school, even within its traditional domain, gives substance to the question. Resnick (personal communication, December 2, 1988) suggests that one might need to return to some more fundamental notions such as the general sense of oneself as being empowered to reformulate a question, add to a problem, interpret information, and ask for and give help.

Moreover, it is worth asking to what extent the competencies needed in the technological workplace are really new or different, and whether the differences have as yet been identified. For example, the competencies listed by Levin and Rumberger (1989) as necessary to function effectively in newer work settings are nearly all competencies that workers displayed in the milk processing factory, a very traditional work setting, studied by Scribner (1984, 1986) and described in some detail below. Perhaps current studies on the changes in the workplace being brought about by complex technologies (personal communications: Scribner, October 21, 1988; Tanner & Brun-Cottan, The Workplace Project, January 19, 1989) will provide further insights on the new requirements for workers.

Another question that needs to be asked is what is the extent to which the work environment, with its increasing complexity, will come to resemble more and more the academic strand of education. This may be particularly true of middle and upper level jobs. Diagnosing a problem, gathering and interpreting information and applying it to a problem situation, reporting on the problem and its solution, and using supporting evidence to strengthen the report, all take on the hallmarks of academic work, particularly when the operations and functions involved are heavily based on symbols and require considerable knowledge and interpretation. Even such functions as inventory management, product control, and costing, rather than relying on managerial expertise, are now computerized through programs that are based on formal conceptual systems, resembling such traditional school subjects as mathematics or grammar (Vaughan & Berryman, 1989). One might speculate that the separation between school and work is actually shrinking, that school learning will become more functional for effective job performance as the application of technology continues to make the work environment more symbol-dependent. More empirical research is needed before such a conclusion can be reached. In any case, large numbers of people in school are not acquiring the very competencies that school is designed to teach and that may become more and more valued in the workplace. (See, for example, the discouraging findings on students' learning of higher-order skills in mathematics reported in Dossey, Mullis, Lindquist, & Chambers, 1988, and the equally dismaying lack of writing competence reported in Applebee, Langer, & Mullis, 1986).

The Skills Hierarchy Fallacy

A major concern is whether skills of the type on Levin and Rumberger's list might not be subjected to the same problems that have plagued skill training in general (Resnick, personal communication, December 2, 1988): (1) decomposing any competency to its smallest parts and teaching each part separately on the assumption that, if each subskill has been learned, all the subskills can be put together and the competency will have been acquired; and (2) teaching individual competencies or skills out of context on the assumption that each will then be applied appropriately in context. Thus, earlier lists of needed skills or competencies have often been translated into educational and training programs that posit some hierarchical skills structure, decomposed so that subskills can be taught one at a time until mastery is obtained, whereupon the next subskill in the hierarchy is taken up. The isolated subskills, often freed of any context, have become reified as individual "building blocks" of expertise to be used as the basis for instruction, either in the workplace or in school.

One major stream of recent cognitive science research has been the analysis of the performance of effective workers in contradistinction to developing abstract skills hierarchies. Such studies of performance, ranging from analyses of school-related formal learning tasks to complex technical occupations, have provided important insights and led to some very successful training programs (Glaser & Bassok, 1989). Gott (1984, pp. 79-82) makes the point that, for such technically demanding jobs as Air Force personnel dealing with complex and specialized aerospace systems, traditional literacy skills are imprecise and limited in their usefulness. Instead, the job skills that appear to be linked to proficiency consist of competencies that integrate specific job knowledge and skills and more general habits and ways of approaching problem situations. For example, competent avionics technicians possess effective mental models for large systems (F15 radar antenna, antenna test stations) and their electronic components; engage in troubleshooting characterized by planning, ability to trace circuit paths (rather than just swapping boards), and a facility in handling technical orders; have and use knowledge of the interrelationship between the test station and the electronic unit; understand logic gates; and are efficient in meter reading. This sort of list, developed out of a careful analysis of effective performance in a particular work situation, is an interesting combination of skills that are clearly job specific and skills that would be considered more general.

One lesson from this work is that one needs to understand the contexts and settings in which the skills and competencies are displayed. Defining or describing the features that appear to characterize effective workers in the modern workplace has emphasized the need to understand to what extent these are skills that can be taught through traditional schooling and what sorts of education programs are likely to engender them.

The Changing Workforce

Not only is the workplace changing, so are the numbers of new entrants, their characteristics, and their average age. These demographic shifts in the labor force are reasonably well recognized (see Kutscher, 1987). Less well understood are the implications for designing vocational education and other training programs that are effective in developing this country's human resources.

Decreasing Numbers of Entering Workers

Until the baby boom children who are now beginning to swell elementary school enrollments once more enter the workforce, the number of workers entering the labor market will be decreasing, even taking immigration into account. Silvestri and Lukasiewicz (1987) estimate that between 1986 and 2000 there will be only about half the average annual rate of increase that occurred over the previous fourteen-year period, 1972 to 1986. One implication is that, if the economy is to flourish, a larger percentage of entering workers will need to be educated for technologically demanding jobs than would be the case during times of labor surpluses.

The Multicultural Workforce

The complexion of the labor force will be changing as well in that it is expected to become increasingly minority and female. Minorities—blacks, Hispanics, and Asians—are projected to account for nearly sixty percent of the labor force growth, while women will make up nearly two-thirds of the net increase. Also, unless current social trends are reversed, more young people will be coming from unstable homes and conditions of poverty; others will be disadvantaged because of their inadequate knowledge of the English language. Typically, these are populations by which the schools have done most poorly. Vocational education programs are no exception, with the economy having in the past relied for native-born majority males to fill occupations of the greatest sophistication, as well as status and pay. The Perkins Act, intended specifically to increase the access of "special populations" (e.g., the economically disadvantaged and at-risk youths) to high-quality vocational education programs and promote sex equity, has not been very effective in either respect. The National Assessment of Vocational Education (Wirt, 1989) found that

> the quality of vocational education available to students in poor schools is significantly lower than that available to students in more affluent communities. Students in schools in the lowest quartile, as measured by average family income, student academic ability, and socioeconomic status, are half as likely to have access to an area vocational center as other students. They are also in schools with less than half the number of advanced vocational courses. . . . At community colleges, black students earn thirty percent fewer credits than white students and fail to earn a degree or certificate at a rate twenty percent higher . . . fifty-one percent leave before completing their program. Hispanic students average sixteen percent fewer credits than white students. . . . Dropout rates are significantly higher for the most economically disadvantaged students. . . . Most grants designed to promote sex equity are too small to carry out any but the most marginal activities. The median grant to a school district is $3,600 and three quarters of awards are $9,400 or less. (pp. 4, 7-8, 13)

Vocational education may not do a worse job with the populations of concern than does education in general, but the hope that it would provide more effective preparation has clearly not been realized. These populations remain, on average, badly served. One reason for this paper is the potential of cognitive science research to bring about an improvement in this unacceptable situation. For, unless a better fit is developed between educational programs and the learning styles and learning capacities of growing proportions of the country's population, the potential of the available human resources will be greatly underdeveloped, with adverse consequences for both the individual and the economy.

Retraining Older Workers

Third, as occupations continue to shift in type and functions, older workers will likely reenter or have to undergo training and education to keep up with or change occupations. This demand is already reflected in the changing population and mission of community colleges, many of which are heavily involved in retraining and upgrading the skills of older workers (Hankin, 1989; Warren, 1985). Older workers bring different competencies to education and some of the same needs, and these must be understood and served as well.

Changes in the World of Education

The last decade has been characterized, first, by a spate of reports critical of education and its outcomes and, second, by a wave of reforms designed to address the criticisms and improve the outcomes. Generally, the criticisms were leveled at the weak curriculum of the schools and the inadequacy of students' coursework, the insufficiency of instruction, and the mediocre performance of students on achievement tests, especially when compared with their counterparts in other countries. (Most prominent among the national reports are the ones produced by the National Commission on Excellence in Education, 1983; the Task Force on Education for Economic Growth, 1983; the Twentieth Century Fund Task Force, 1983; and the National Science Board Commission on Precollege Education in Mathematics, Science, and Technology, 1984.) Carnoy and Levin (1985, p. 261), citing Edson (1984), point out the similarity of the criticisms—and the recommendations for reform—of the 1980s to those of nearly a century earlier made by the *Committee of Ten Report* under the leadership of Charles Eliot, president of Harvard University. These are greater rigor and increases in course requirements to offset decline in academic standards, longer school hours and more stringent standards in selecting teachers to improve instruction, and greater emphasis on excellence to reestablish U.S. competitiveness vis-a-vis other industrialized countries.

Several of the reform reports of the 1980s also focused on the unpreparedness of today's high school graduates for tomorrow's world of work (e.g., Committee on Science, Engineering, and Public Policy, 1984; and the reports cited above). Although vocational education itself was not directly the subject of these criticisms, it was an indirect target nevertheless, since the implications if not outright recommendations in most of the reports were for more rigor, usually translated to mean more academic courses. Indeed, almost all states responded by mandating increases in academic course credits required for high school graduation, particularly in mathematics and science (Blank & Espenshade, 1988; Goertz, 1986). One effect has been to reduce the time available for vocational education courses. Indeed, these courses appear to have been the main casualty of educational reform. A recent study of six diverse states (Clune, White, & Patterson, 1989) suggests ". . . that in schools affected by the increased high school graduation requirements (those with a significant number of low- and middle-achieving students), about twenty-seven percent of students are taking an extra math course and thirty-four percent an extra science course" (p. 33). There are differences of opinion on whether these courses are better than the ones they replaced; certainly some educators queried by Clune and his coworkers thought not, as their comments show:

> It devastated our vocational program. We curtailed offerings of vocational courses. It creates work overload and conflicts for our students.
>
> . . . For the noncollege-bound students, the requirements are, in all honesty, doing a poor job . . .
>
> The big disadvantage of the increased requirements is that there are no provisions for those students who cannot do well. There is no vocational track with remediation in the basics.
>
> They just don't address the needs of the kids not going to college. It's a real problem for those who just want to get a job after high school.
>
> Teachers of electives and vocational education feel less valued than in the past. (pp. 21-22)

A set of intensive case studies of three comprehensive high schools (Selvin, Oakes, Hare, Ramsey, & Schoeff, 1989) comes to similar conclusions. The investigators found that relatively healthy and rich vocational education programs had been severely cut back and lost prestige at each of the schools as a result of increased stress on academic courses, to the point of being in danger of withering away completely.

Kirst (personal communication, November 17, 1988) reports that enrollment in vocational education programs has dropped by twenty percent in California, in large part as a result of the increased academic requirements which tend to affect students in the thirty to eighty percent performance range. Although national data through 1987 indicates that the declining number of youths of high school age was an important source of enrollment decline in vocational education (National Assessment of Vocational Education, 1989), the academic reform movement appears to have accelerated the decline.

One response has been the recommendation that the rigor of vocational education be increased and the subject matter content be broadened to the point where the distinction between academic and vocational subjects is blurred. Indeed, some critics—in the spirit of earlier reform movements—see this approach as appropriate for most students, not just those traditionally enrolled in vocational education. In any event, this is a time of reexamination for vocational education.

To summarize, the expectations for vocational education continue to be beyond what most programs are delivering. These expectations include the following:

- Graduates with acceptable general literacy skills, which continue to be redefined to encompass increasing levels of competence in language, mathematics, and general cultural knowledge;
- Acquisition of habits and dispositions that characterize effective workers;
- Effective education for disadvantaged students that will open equitable opportunities for employment and/or further education;
- Training for academically less able youths to allow successful entry into the adult labor market without foreclosing the opportunity to enter higher-status jobs; and
- Training future employees in very specific and often very complex job skills.

The concern of this paper is to examine how current research in cognitive science can contribute to the realization of these diverse and ambitious goals and to ensure that the efforts to reform vocational education be informed by current knowledge about how people learn to be effective workers—effective both in their own personal terms and with respect to their performance on the job.

SCHOOLING AND WORK

Vocational education has its origin in the expansion of secondary education around the turn of the century and the perceived need to provide agricultural and industrial training for young people who left school because the academic curriculum—the only one offered by the high schools originally created for an elite student body—was irrelevant to them. The response was to create a separate track relevant to the preparation of workers who would go into agriculture and industry; this educational need was deemed so important to the nation that in 1917 the Smith-Hughes Act was passed providing federal aid for vocational education.

This early history continues to echo in contemporary debates concerning vocational education and academic schooling. At issue is the distinction between knowing what (knowledge) and knowing how (doing), the common view being that this distinction is mirrored in the learning of canonical knowledge through formalized instruction based on textbooks, lectures, and other types of structured, usually print-based materials, and learning by doing through hands-on experience. As noted, the education system has adjusted by offering separate tracks, encouraging students to select either "preparation for doing" (i.e., vocational track, trade schools, and community colleges) or "preparation for knowing" (i.e., academic track and college/university). Unfortunately, the choice is not always the result of extending equal opportunity to students of different backgrounds (Oakes, 1985), nor is it without stigma. Generally, the vocational track is thought of in regard to less intellectually prepared individuals, whether young students or older learners, and these turn out to be overrepresented among minority and poor population groups. Oakes (1986) points out that this formulation has roots going back to the inception of vocational education and carries with it negative status connotations that continue to this day. In comprehensive high schools, vocational courses are perceived to be second class at best and a dumping ground at worst, with the faculty teaching them and the students enrolled in them held in similar low esteem (Selvin et al., 1989).

However, goals and expectations for schooling shift periodically. Vocational education is criticized for reifying a second-class educational track that not only forecloses access to high-status professions but has little pay-off of any kind. The academic and general tracks are criticized because they do not provide young people who are not college-bound with an adequate preparation for the workplace. From time to time, this criticism of formal education—vocational and academic both—has extended beyond inadequate preparation for the workplace to include inadequate preparation for citizenship and family responsibilities as well. As a result of the criticisms, there have been attempts to integrate hands-on education with academic courses and academics with vocational education. During periods when academic achievement has been deemphasized in favor of learning to do as a goal for everyone, the schools have responded by making a few manual skills courses mandatory—home economics for girls, shop for boys—as part of a secondary school education. At present, because schools are being criticized for their lack of academic rigor, more mathematics and science courses are being introduced into vocational programs to meet increased high school graduation requirements.

Basic Skills

Both learning to know and learning to do are supposed to require the acquisition of a set of basic skills before further education can take place. Though there is a debate about what these basic skills are, there is general agreement that there is a core body of knowledge and skills that must be learned as a foundation for all other learning. At the most rudimentary level, teaching of the basic skills generally concentrates on the acquisition of reading and arithmetic skills, on the generally accepted principle that these are prerequisites for deciphering and dealing with the most elementary artifacts of the culture.

Even so, by no means have the schools succeeded in ensuring that all young people acquire these skills at a level that makes them reasonably functional in American society. For example, urban disadvantaged youths at the fifth percentile of achievement were reading at the fourth grade level of skill. Although compensatory programs are narrowing the gap somewhat, Sticht and McDonald (1989), using NAEP assessments, estimate that at the present rate of progress it will take eighty years to raise the median reading score of urban disadvantaged 17-year olds to the overall median score of the 1984 17-year old population.

However, there are reasons to question the basic premise of "first things first." Accumulated research findings on how people learn and use basic mathematical and reading skills are raising doubts in the wider educational community about the commonly accepted skills hierarchies (see Bracey, 1989).

Arithmetic on the Job

The evidence is particularly illuminating in arithmetic. It appears that many individuals, even otherwise illiterate individuals, are able to acquire arithmetic skills and generate their own efficient paradigms to solve arithmetic problems in the work context or in real life outside work. They develop these paradigms, which may be quite different and more efficient than the formal algorithms learned in school, both through watching other workers and through their own invention. Despite these learned methods, they are unable to solve analogous problems which are posed to them in a formal schooling format.

For example, Carraher, Carraher, and Schliemann (1985) studied the computational skills of children who sell things in the street markets of Recife, Brazil. These children accurately make frequent and quite complex mental calculations connected with their commercial transactions, but failed the same problems in a formal school-type test where paper and pencil were used. The authors conclude that "daily problem solving may be accomplished by routines different from those taught in schools . . . attempts to follow school-prescribed routines seemed in fact to interfere with problem solving" (p. 28). These researchers see their results as providing evidence for the thesis of Luria (1976) and Donaldson (1978) that "thinking sustained by daily human sense can be—in the same subject—at a higher level than thinking out of context " (p. 27).

Carraher (1986, p. 527) presents further evidence in a study that contrasted the use of mathematical scales by Brazilian construction foremen with limited schooling to the use of mathematical scales by Brazilian school students. The daily work experience of the foremen enabled them to outperform the students in a series of problems on scale drawings, whereas the students failed to improve their performance through use of the applicable proportions algorithm they had been taught. In the synthesis of her findings, Carraher interprets that these differences arise from the different contexts in which the learning about ratios and proportions were taking place. This leads her to suggest that the mathematics teaching characterized in formal schooling tends to overlook the importance of meaning in mathematics, which lowers students' performance.

Arithmetic in Everyday Life

Disjunctures between everyday use of mathematics and school-based mathematics are also found in nonwork settings. Anthropologists who have studied people's everyday use of arithmetic observe that they frequently use cues available in the environment in their solutions. For example, in a study that focused upon the arithmetic practices of dieters as they attempted to control food portions and calories, Lave (1988a) found one dieter using an ingenious geometric solution in order to avoid having to multiply fractions. (He dumped two-thirds of a cup of cottage cheese onto a cutting board, patted it into a circle, and cut it into quarters to get three-fourths of two-thirds—the allotted portion.) De la Rocha (1985) concludes in her related study that the dieters' actual situations presented them with a new set of problems and possibilities that allowed them to construct the knowledge they needed for their immediate purposes: "At once constrained and inspired by the circumstances, the dieters devised a set of customized tactics that frequently supplanted the practice of precise measurement and depended on contingencies in the environment . . ." (p. 194).

The same researchers also have observed people's arithmetic-related behaviors as they shop for groceries (Lave, Murtaugh, & de la Rocha, 1984). They point out that the problem formulations themselves as well as the solutions (e.g., before unit pricing and deciding which is the better buy of two different brands of similar cheese) are influenced by the location and the setting, that is, the grocery store and how the products are displayed, as well as the shopper's intent. Moreover, shoppers tend to carry out multiple calculations in ways that do not match the conventional teaching of arithmetic procedures in school, which are based on a linear progression of operations. This leads Lave et al. to question whether the usual approach to arithmetic problems is useful pedagogically:

> It may be necessary to give up the goal of assigning arithmetic problems to unique locations—in the head or on the shelf—or labeling one element in a problem-solving process as a "calculation procedure," another as a "checking procedure." It may even be difficult to distinguish the solution from the problem. (pp. 88-89)

Learning to Read and Literacy

The suggestion that context influences performance applies more broadly than just to mathematics. A similar thesis is sustained by Sticht (1987, sec. 2.16) who found that "marginally literate adults in a job-related reading program made twice the gain in *job-related* reading than they did in general reading," that is, they did better when a meaningful context was provided for the text.

Investigations into early reading and the development of reading comprehension demonstrate that learning collaboratively with others together with modeling of effective performance also provide a good learning context. Elementary school students in Palincsar and Brown's (1984) classes became efficient readers by interpreting texts together, using stratagems explicitly displayed by a more skilled reader (the teacher). Though the teacher provided some guidance and feedback and participated in the text interpretation, the students constructed the meaning of the passage together through "reciprocal teaching," with students taking turns as discussion leader. While students carried on some spontaneous discussion and argument, they were guided by the teacher to concentrate on four interpretative activities engaged in (though usually not consciously) by good readers: summarizing, questioning, clarifying, and predicting. These activities were always done in the story or reading context, never as separate skill exercises. As students became more expert at text interpretation, the teacher faded into the background and students took on the responsibility for their own learning from text. A similar program that had good results was with disadvantaged 13- and 14-year olds who were reading at the third grade level (Brown & Campione, 1984).

Learning in Science

Cognitive science research is providing similar evidence about the connection between meaningful context and learning in other fields as well. Such evidence, even though it comes from fields traditionally considered academic, is not irrelevant to a consideration of education for work. First, as noted above, more and more jobs are changing to require greater familiarity with abstract representations and the ability to manipulate symbols as contrasted to earlier manufacturing processes visibly involving concrete objects. Such reliance on formal operations is an inherent characteristic of the academic disciplines. Moreover, there are built-in similarities in human cognitive functioning no matter the domain.

Researchers have found that even very young students bring to the classroom their own experiential knowledge about the workings of the world around them, and that this experiential knowledge is very difficult to displace through such formalized learning as the memorization of facts, concepts, and formulae out of the context of real world experience. Driver, Guesne, and Tiberghien (1985) give examples of children's conceptions of light, electricity, heat and temperature, force and motion, the gaseous state, physical and chemical transformations, and the earth as a cosmic body. The ideas children have in these domains are personal (i.e., constructed by individuals out of their own experiences and interpretations), coherent in their own terms, and resistant to change through traditional school instruction. Interestingly, there are some general patterns in the types of ideas that children develop even when growing up in different countries, though as children grow older these ideas are modified by the local culture.

The research on science learning does not apply to young children only; similar findings come from investigations dealing with what is traditionally considered higher level academic learning. For example, students in introductory college physics courses designed for physics majors can solve "book" problems in Newtonian mechanics by rote application of formulae, but—even after instruction—revert to naive pre-Newtonian explanations of common physical situations (Champagne, Klopfer, & Anderson, 1980; diSessa, 1983;

White, 1983, 1984). To support this, the Committee on Research in Mathematics, Science, and Technology Education (1985) found that "various strong convictions, which are often reinforced by unaided common-sense perception (as in naive accounts of forces acting on the movement of objects on an inclined plane), become intertwined with new learning and inhibit its progress" (p. 8).

It appears that what people know through experience exerts a powerful influence on what they learn in the classroom. When this intuitive "knowledge" runs counter to the canonical knowledge held by experts in the field, it poses a considerable barrier to relearning or new learning, leading individuals to wrong solutions of unfamiliar problems and even to screening out or misinterpreting evidence contrary to their preformulated perceptions. In this kind of situation, restructuring people's naive conceptions to accommodate more sophisticated and powerful concepts requires their exposure to repeated and various experientially based counter-examples that will lead them to question and finally reformulate their own notions to fit better with the new evidence.

The Dysfunctionalities of Schooling

As the examples given above illustrate, recent cognitive and anthropological research has documented the fact that people learn differently on the job and through experience than they do in formal school settings and, just as important, that they use what they know differently. In her 1987 Presidential Address to the American Educational Research Association on learning both in and out of school, Resnick (1987a, p. 16) identified four classes of discontinuities between education as practiced in school and learning and its application in daily life and work: (1) the focus of school on individual performance as contrasted to socially shared performance in most nonschool settings; (2) the school model (particularly prominent in testing) of unaided thought, whereas work (especially in the higher skill occupations) makes available and even requires the use of cognitive tools; (3) the emphasis of school on symbolic thinking to the exclusion of the objects and situations that aid problem formulation and solution in real life and at work; and (4) the attempt to inculcate general skills and knowledge as contrasted to the situation-linked knowledge and skills that make for effective performance outside school.

Thus, schools present normative learning opportunities which were originally created to enable students to gain general skills. The underlying assumption is that students will be able to transfer these skills to a variety of work situations. Unfortunately, instruction in these skills all too often takes place through the practice of isolated subtasks in which the emphasis is upon satisfactory repetitive performance rather than on use in appropriate contexts. In many schools, students who are not immediately successful have little opportunity to manipulate or reason using the very symbols that form the substance of the basic skills instruction.

Not surprisingly, students emerge from school handicapped in the workplace where they face a changing world of complex technologies demanding the use of problem solving skills that they have never had the opportunity to learn. To counter these young workers' seeming incompetence, industries develop turn-key operations and step-by-step manuals that further disable students/workers by removing any possibility of their developing in-depth understanding of the problem solving processes involved in their particular work assignments.

So far, in the school-work schema of learning, little attention has been paid to the kind of learning and reasoning people actually do everyday. As the above examples illustrate, when one steps outside the classroom and looks at genuine problem solving in a variety of real life situations, the students/workers appear far from incompetent. Indeed, their situated problem solving activities are far more complex than one would be led to expect based upon assessment of their textbook learning. Notes Resnick (1987a):

> . . . evidence is beginning to accumulate that traditional schooling's focus on individual, isolated activity, on symbols correctly manipulated but divorced from experience, and on decontextualized skills may be partly responsible for the school's difficulty in promoting its own in-school learning goals. (p. 18)

Implications for Instruction

Clearly, many people are able to invent ingenious, common-sense solutions rather than using algorithmic, school-taught solutions for arithmetic problems encountered in real life. Does this mean that individuals would be better off not to be taught the formal algorithms? What happens when work circumstances change so that highly situation-specific skills no longer apply? None would argue that the power conferred by the formal algorithms is irrelevant; rather, the issue is how to help people recognize and utilize that power. Carraher et al. (1985) conclude that, even though children are capable of developing their own computational routines, these routines have limitations that are addressed by the conventional system of written computation developed by the culture:

> The sort of mathematics taught in school has the potential to serve as an amplifier of thought processes. . . . school math routines can offer richer and more powerful alternatives to math routines which emerge in nonschool settings. The major question appears to centre on the proper pedagogical point of departure. . . . We suggest that educators should question the practice of treating mathematical systems as formal subjects from the outset and should instead seek ways of introducing these systems in contexts which allow them to be sustained by human daily sense. (p. 28)

Similarly, Pea (1987) suggests that, in general, concepts, strategies, and skills should be taught "in a problem-solving context where their functions are rendered apparent. Such functional presentations and the emphasis on learning by doing will make more likely that the knowledge will be accessed and transferred to new problems" (p. 652).

Driver et al. (1985) come to similar conclusions regarding children's learning of science. The knowledge and ways of knowing that characterize science are powerful, but they are not generally acquired through traditional classroom science lessons. The time devoted to a lesson or even a series of lessons on a particular topic hardly suffices to change children's strongly held ideas that they bring with them to school. Traditional curriculum design usually is based on a conceptual analysis of the subject matter but ignores what is already in the learner's head. The result of this is that children can play back memorized canonical knowledge and conceptions but return to their own ideas when confronted with unfamiliar questions or nonroutine problems. Driver et al. suggest that instruction must be designed to bring about conceptual change through "(1) Providing opportunities for pupils to make their own ideas explicit . . .; (2) Introducing discrepant events . . .; (3) Socratic questioning . . .; (4) Encouraging the generation of a range of conceptual schemes . . .; [and] (5) Practice in using ideas in a range of situations" (p. 28). A recent report on science education in elementary schools (Bybee et al., 1989) provides an instructional model to guide classroom teachers away from stressing memorization of facts toward teaching for understanding and application of science knowledge.

These suggestions, though they focus on science, could be taken as a prescription for any kind of effective learning. They stress helping individuals make sense of their environment through staged experiences and under the tutelage of a more experienced mentor—strategies that are embedded and used quite naturally in good apprenticeship situations. Starting with the learner's state of knowledge is in contrast to the usual top-down curriculum design and classroom teaching in which the knowledge of experts is encoded into instructional materials suitably "simplified" for the learner (Wenger, 1988, p. 24).

An example of integrating the teaching of general school-based skills with practical knowledge is provided by an experimental course designed to prepare at-risk youths and adults with inadequate backgrounds (e.g., low literacy skills—at fifth through ninth grade level—and females with low technology skills) to become electronics technicians. The course was based on two principles derived from military training research (Sticht, Armstrong, Hicky, & Caylor, 1987) and from cognitive science, which were that

> Expert electronics technicians draw as much on their understandings of equipment as functional systems as they do on traditional basic electricity and electronics theory. . . . Basic skills (literacy, mathematics, problem solving, troubleshooting) are interrelated capabilities that draw upon a common knowledge base in a person's mind. . . . Hence, improvements in basic skills can be accomplished by improving a student's knowledge in a domain area . . . (Sticht, 1987, sec. 5.4)

Yet, technical training programs in both military and civilian settings tend to screen people using basic skills tests and to teach basic skills as prerequisites. This results in the "front-loading" of basic electricity and electronics courses with decontextualized basic skill or literacy programs before providing hands-on experience. In contrast, the experimental course explicitly went from the concrete to the abstract, from the specific to the general, from practice to theory, and from the familiar to the unfamiliar. In order to develop mental models of electronic equipment, the course started with hands-on instruction using simple and familiar electrical equipment: flashlights, table lamps, curling irons, portable radios and tape players. Students explored the devices, starting with the flashlight, in hands-on fashion, then worked along with the instructor to learn how to examine the equipment, think about it as a system, and understand its functions. Reading, writing, diagramming, mathematics, problem solving, and troubleshooting were integrated into the teaching of technical knowledge. As the course progressed, more abstract representations and complex calculations were introduced, always in a functional context. Sticht (1987, sec. 5.13) reports that students, who otherwise would most likely have been screened out of traditional electronics training, were learning basic electricity, electronics, and basic skills. Like Driver et al. (1985), the author concludes that effective courses

- Use the knowledge that students bring with them to build new knowledge;

- Integrate the instruction in domain-specific knowledge and skills with reading, writing, arithmetic, and problem solving rather than offering decontextualized basic-skills remedial programs; [and]

- Use learning contexts, tasks, materials, and procedures that mirror as closely as possible subsequent work tasks and situations, so that students are clear about what they are to learn and why, [and] how the knowledge and skills they are acquiring will be applied.

The argument is not that abstractions should not be taught; it is that they will be better understood when their meaning is explored in detail within specific situations in which they apply. The Three Mile Island accident is a clear illustration of the difficulties that can occur when instruction does not integrate theory, systems knowledge, and site-specific operations and procedures. The body investigating the accident, The President's Commission on the Accident at Three Mile Island, concluded in the publication of that name (Volume III) that much of the fault lay with the inadequate training program:

> The replacement operator program which prepared reactor operator candidates for licensing was done essentially on a self-study basis. Although nine months were devoted to this program, little emphasis was given to theory, application of the theoretical to the practical, or principles of operating and casualty procedures. Required study did not cover thermodynamics and such concepts as saturation, enthalpy, decay heat production, or solid system operation. Rather, emphasis was on systems, equipment, and procedures. Operator trainees were not provided with a fundamental, comprehensive understanding of their reactor plant design and operation which would enable them to recognize the significance of a set of circumstances not explicitly predicted by the operation procedures and which would lead them to place the plant in a safe condition.

Thus, operators learned how various pieces of equipment worked, how plant operating and safety systems worked, and how to apply preconceived, stepwise procedures to various abnormal and emergency situations. They were not taught or expected to know how or why a specific nuclear power plant would respond to different types of failures, and they lacked the basic understanding necessary to deal safely with the relatively minor failure which occurred. (See also the research conducted for the Air Force Human Resources Laboratory by Lesgold et al., 1986).

It is not a question of either practical knowledge or theoretical knowledge, it is more a matter of blurring these artificial distinctions so that apprentice workers are provided with an opportunity to understand the problem solving tasks that they are given to accomplish. Apprentices need opportunities to gain both practical experience and situationally specific, theoretical understandings in a combination of ways (e.g., on site/in a simulation/through formal instruction) that are relevant to the specific work situation.

The Track Record of Vocational Education

Connecting school-learning to the real life context of work has been the essential motivation for vocational education. A key ingredient is the simulation of work contexts in which students can acquire and practice both the basics and the specific skills thought to be necessary for a particular occupation. Clearly, such an approach requires that the simulation or work experience offered through vocational education programs provides opportunities to address problem situations that are likely to be encountered later on in an actual job.

From the outset, regardless of swings in general educational philosophy from progressive education to academic rigor to relevance to "back to the basics," learning through doing has been an express component of vocational education—even before cognitive scientists documented its effectiveness. Has that made vocational education work? Grubb (1979) suggests four criteria for evaluating the effects of vocational education programs: (1) to what extent they segregate lower-class and minority youths into tracks that foreclose educational and economic opportunities, (2) their economic returns to individuals enrolled in them in the form of earnings and reduction of unemployment, (3) their effects on overall employment patterns as contrasted to employment effects on those enrolled in the programs, and (4) social effects in terms of smoothing the transition from school to work. An underlying goal is the acquisition of general and work-specific skills which enables individuals to obtain and advance in desirable jobs, relevant to criteria (2) and (4). This is particularly important for disadvantaged youths, relevant to criterion (1). If the effectiveness of vocational education programs is to be judged by the acquisition of these skills—in whatever combination—and by the success experienced by vocational education students in entering and maintaining themselves in productive jobs, results have been decidedly mixed (Grasso & Shea, 1979). Graduates of vocational programs appear to do no better in finding jobs than their peers coming from other programs (Mertens, McElwain, Garcia, & Whitmore, 1980) or, in the case of California, even high school dropouts (Stern, Hoachlander, Choy, & Benson, 1986). Moreover, the National Assessment of Vocational Education concluded that the performance of most vocational education programs in raising academic skills is poor and that considerably fewer than half of all vocational education students obtain good jobs related to their vocational training (Wirt, 1989, p. 8).

Yet, there are instances of success. Math-intensive vocational courses such as business math and vocational math produce math achievement close to that of traditional mathematics courses, and this holds true for students of low ability as well as for students of high ability. Also, despite the generally discouraging picture regarding job entry, success has been high in some selected occupations, particularly in the clerical and secretarial fields. If the general proposition regarding the effectiveness of experience-based learning is correct, and vocational education espouses this approach, then what are the reasons that many programs fail? And what distinguishes the successful ones? Two conjectures might explain the success of vocational education programs in the clerical and secretarial fields. First, the skills that are taught (both technical and general) are useful in many different job settings: typing, word processing, answering the telephone courteously and informatively, setting up filing systems, anticipating the supervisor's needs, setting priorities among assignments, and running an efficient office. Second, school itself represents an appropriate model for the kinds of structures in which many clerical and secretarial personnel work—hierarchical and bureaucratized. The school setting in which the teacher is supervised by the principal, who is supervised by the administrator, who has policy set by the school board and the state, represents a hierarchical structure that determines not only what the students are to do and how they are to behave, but also how they are to be judged. Similarly, a secretary or clerk works for a supervisor who has several layers of supervisors above him or her, and these layers structure the secretary's tasks in a way similar to the way that school structures tasks for the student, with neither the secretary nor the student having much power to influence the nature of the work. Also, learning to please the teacher is a good way of learning how to please one's supervisor, and learning to get along with one's fellow students at the same time as one competes with them is good preparation for relating to one's fellow workers later on.

Perhaps a more convincing example that occupation-related education can work is provided by the forerunner of all vocational education programs—agricultural education and training. Without question, this has been a great success story. Agricultural workers, particularly those who went on to advanced training at the university level, have implemented sophisticated techniques that have made farming increasingly productive and changed it from a labor intensive to a capital intensive industry. It is to be noted that these successes were made possible through a whole system of agricultural research, development, and demonstration farms, which were supported by a two-pronged system of education that provided college level training to prospective farm managers, while sending into the field extension agents who kept individual farmers in touch with the latest innovations and convinced them that these would work for them in their situations. Of course, there have been adverse consequences to the tremendous increases in agricultural productivity. While the research and the training and dissemination systems that implemented the research were highly effective in making individual farmers and the agricultural sector successful, they also had the effect of displacing millions of farm laborers, thereby generating social problems of unemployment, poverty, and cultural dislocation that still have not been resolved. The farm workers who were displaced lacked the education needed to enter skilled jobs in industry. Only the large industrial expansion during each of the two world wars which absorbed many of these unskilled laborers into the defense industries and the armed forces relieved the situation. The history of the effects of agricultural training supported by R&D and the successful implementation of innovations is perhaps a useful paradigm for thinking about the effects of the current revolution in technology, communications, and robotics. Instead of war, the response to the problem of a decreasing demand for low skilled workers due to the increase in automation, robotics, computerization, and related communications technology needs to be effective education for the workplace.

There are at least two reasons to be optimistic about the possibility that reformed vocational education may be able to play such a role. One is that the technology that is revolutionizing the workplace is also available for revolutionizing education. Raizen (1988) summarizes the educational potential of computers and associated communications technology as follows:

- Instruction can be tailored to the individual needs and learning style of the student ... [and] take into account the knowledge that individuals have and the pace and learning method that best suits them ... both student and teacher receive immediate feedback.

- Computers can be used to create new learning environments. ... This capability allows students to explore ideas and hands-on learning in ways never before possible.

- Computers can represent knowledge in many different ways ... the representations can be linked, so that students learn to understand their relationships and which representation is most usefully employed to analyze a particular problem.

- Computers can provide powerful intellectual tools for both students and teachers. . . . Problem exercises can be based on real data rather than being artificially constructed . . . .

- Computers in association with telecommunications technology can create learner networks apart from the physical location of the learner. . . . Specialized instruction can be brought to any school . . . out-of-school learning sites can be connected to schools, institutions of higher education, or experts in industry . . . individuals of different competencies can collaborate on common projects.

- Computers can motivate learning. The computer is an ever-patient tutor. The open learning environment that the computer makes possible could demonstrate to nearly all students the joy of learning and the power of knowledge. (pp. 32-33)

Unfortunately, particularly for vocational education students, in most schools the computer is used in its narrowest educational applications: drill and practice to learn basic skills, and such job-specific skills as low level programming (rapidly becoming obsolete) and word processing. (Excluded from this criticism are programs that focus on training for jobs using computers as an integral part of the work such as computer-assisted design, computer-assisted manufacturing, or troubleshooting computer-linked equipment.)

The second reason for optimism is the reason for this paper, namely, that cognitive science has been uncovering more and more about what makes for effective performance, how people learn, and what facilitates and impedes learning. Cognitive psychologists have been modeling the processes going on in the individual learner's head. Sociologists and anthropologists have been observing learning in social groups and learning in context, that is, using the given physical setting and available tools as part of the structure of learning. The development of technology and cognitive science research have been intimate partners. Not only has the computer enabled the development and testing of cognitive theory and the construction of effective training programs, it may even change the questions through its influence on the nature of work and, hence, on the competencies needed by workers. Some researchers see the computer's effects as more fundamental still, forecasting that it will become a tool for reorganizing the knowledge and skills structures in people's heads (Pea, 1986).

Reformulating vocational education will require the more productive use of available learning technology integrated with the developing knowledge of the learner and effective learning contexts. The discussion that follows summarizes the major themes which characterize recent research in cognitive science, focusing on the relationships between learning to know, learning to do, and doing.

LEARNING AND WORK

Evidence is accumulating that the separation between learning to know, learning to do, and doing serves to exacerbate rather than clarify learning impediments in school and on the job. Brown, Collins, and Duguid (1989) state the case as follows:

> The breach between learning and use, which is captured by the folk categories "know what" and "know how," may well be a product of the structure and practices of our education system. Many methods of didactic education assume a separation between knowing and doing, treating knowledge as an integral, self-sufficient substance, theoretically independent of the situations in which it is learned and used. (p. 32)

If this traditional separation between the formal acquisition of knowledge and the experiential learning of competent performance is artificial, then what are the connections between knowing and doing, and how can they be used to facilitate the acquisition of competence? Key research in cognitive science over the last twenty-five years has focused on the individual learner; more recent research has been interested in the learner placed in the physical and social context.

The Individual Learner: Connections between Knowledge and Performance

A fruitful line of investigation has been to observe differences in problem solving skills between experts and novices—how they vary with respect to their knowledge and the procedures they use. In particular, analyses of complex performance have tried to establish links between knowing and doing, that is, how declarative knowledge relates to procedural knowledge; the ways in which the organization of knowledge in the learner's head affect performance; and the role of domain-specific knowledge.

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Declarative Knowledge and Procedural Knowledge

How do declarative knowledge ("knowing what"—the objective of formal education) and procedural knowledge ("knowing how"—usually acquired through experience, but sometimes explicitly taught) interact to increase performance? Lesgold and his colleagues (1986) summarize one current theory as follows:

> Procedural knowledge is thought to evolve from declarative knowledge into automatic processes that "run" without conscious attention, comparable to compiled programs on a computer. . . . Procedural knowledge originates with "weak methods" [domain-independent strategies for problem solving], general methods that try to generate procedures based upon declarative knowledge and the current situation . . . [subsequently] strong, reliable thinking and problem solving procedures arise from the application of weak methods to relevant declarative knowledge, i.e., from appropriate practice. Because both useful and distracting procedures can be formed this way, it is helpful to have an expert critique on-going practice so that only the appropriate procedures are strengthened. (p. 2)

To deepen their understanding of the relationships between declarative knowledge and procedural knowledge, the authors studied the performance of Air Force technicians training to be F-100 jet engine mechanics and F-15 avionics technicians. They observed that even first-term technicians who had little training varied with respect to their performance. Cognitive task analysis revealed that the more highly skilled mechanics did not demonstrate greater general knowledge in the areas in which they performed better. For example, " . . . [T]hey did not display better 'weak-method' capability (such as general strategy planning capability), show greater knowledge of general electrical/electronic concepts, or show greater accuracy or efficiency of basic procedures such as meter reading" (p. 3). Nevertheless, they performed better. They made more correct diagnoses, had better mental models of the systems they were working with (i.e., how components work, what their functions are, and how they relate to the system as a whole), and were more efficient at troubleshooting the specific equipment with which they worked.

Although studying a population with high levels of basic literacy skills, the authors come to similar conclusions regarding literacy training as do Sticht and his coworkers who were cited earlier. They conceive of intelligence—at least in part—as the ability to learn from incomplete instruction, which requires among other things basic competency in reading, communicating, performing simple calculations, and knowing how to learn. One might speculate that the less skilled trainees were not as competent in these basic skills and therefore were having difficulty in learning the job-specific procedures and concepts that their more competent peers had picked up on the job. According to Lesgold et al. (1986),

> If this were true, they ought to have training in basic skills as a supplement. We are inclined to think this is the wrong answer. First, we note that there were no differences between the groups in basic electronics knowledge or procedures, the stuff taught in the schoolhouse. The basic literacy skills anyone knows how to teach are exactly those which are needed for school learning. These people are equivalent on school learning but differ on learning from more informal experiences. Therefore, more basic literacy skills instruction may not help them. (p. 277)

After analyzing the expertise of highly competent technicians, these researchers designed a successful computerized tutoring program posing realistic problems and giving immediate feedback on student responses. This approach, which allows the student to practice diagnosis and troubleshooting, is in contrast to traditional training which consists of having the student carry out, often without understanding, physical steps designed by someone else. Thus, the tutor emphasizes understanding acquired through meaningful practice that provides the appropriate level of the problem and supportive criticism.

Structure and Organization of Knowledge

Knowledge of the subject matter appears to be central to the way experts approach problems. Their greater knowledge allows experts to recognize the general type of problem which confronts them or, if it is a new problem, to try analogies to get at the basic nature of the problem, or to reinterpret it until a solution becomes apparent. Novices, on the other hand, respond to problems as they are presented, using routinized procedures for manipulating those pieces for which they have rote algorithms. They tend to observe surface features and apply formulaic procedures based on those surface features. Much of the difference appears to arise from the way people are able to organize information. Experts, for example, expert chess players, chunk substructures or patterns applicable to solutions, thereby freeing working memory for addressing the deeper structures of the problems. They appear to link salient information and organize it around central principles (Eylon & Linn, 1988). They then select appropriate strategies and actions to address a given problematic situation, and they test these out in order to pursue the best approach. This involves, in addition to structured, domain-specific knowledge and procedures, more general skills in planning and checking one's work. Writing on learning in science, Eylon and Linn summarize: "Research shows that . . . experts engage in more cognitive monitoring than do novices, [possibly] because [novices] lack techniques for evaluating their approaches [or] problem solving may require all available processing capacity, preventing reflection" (p. 280).

However, interpretations of how expertise is developed vary, depending in part on the field of learning being investigated and in part on the disciplinary orientation of the cognitive scientist(s) doing the research. Thus, Glaser (1987b), considering such school-related tasks as developing expertise in reading, verbal comprehension, and arithmetic, gives prominence to the following factors: the *organization of knowledge* and its structure in an individual's head; the *ability to represent the problem in depth* rather than categorizing it by its surface features; *knowing the conditions under which specialized knowledge is applicable* and the problems for which it is useful; *developing schemata for more advanced problem solving* based on the acquisition of additional knowledge; *acquiring automaticity* in handling lower level component skills or subprocesses so as to free working memory for higher level tasks required by a problem; and *facility in managing one's own learning* and problem solving—planning ahead and using time well, checking solutions and monitoring one's performance, knowing what one knows and doesn't know.

With the exception of the last set of skills, this conception of problem solving performance focuses on the relationship between domain-specific knowledge and knowledge schemata, which would include an understanding of conditions and procedures for their use.

Domain-Specific Knowledge

Although much of the research on experts and novices concerns such highly structured fields as playing chess, mathematics, and physics, the conclusions regarding the importance of knowledge within a domain seem to hold in other fields as well. For example, Sticht (1987) emphasizes the importance of domain-specific knowledge in literacy training:

> Applying functional context principles to literacy training suggests that material written on a topic about which the student has developed some prior knowledge will be read and understood better.... According to the human cognitive system model, reading comprehension in a given topic can be improved by increasing one's knowledge base in that area. By coupling this improvement in domain-specific knowledge with instruction in general strategies for reading-to-do and reading-to-learn, it is anticipated that students will develop more generally useful literacy skills and, hence, their overall employability will be improved. (pp. 5-11)

In general, however, the research on experts and novices has not given much consideration to distinctions between high and low aptitude learners. In discussing his view of the acquisition of expertise, Glaser (1987b) comments that the picture he presents "is probably biased by the highly structured domains" in which expertise has been studied, domains that tend to be dominated by individuals with high aptitude. More research is needed on possible variations in learning style among individuals of different aptitudes as they move from being a novice to becoming a competent performer.

Moreover, much of the work on knowledge structures and the relationship of declarative to procedural knowledge omits consideration of the contribution made to an individual's learning by colleagues and by the physical and symbolic tools available in the work environment. On the contrary, environmental requirements have sometimes been seen to act as a limiting factor that sets constraints on the richness of the cognitive models being acquired by experts.

Using the Human and Physical Environment in Learning

Cognitive scientists oriented toward sociology and anthropology who have observed people doing problem solving on the job are developing a completely different line of inquiry (Rogoff & Lave, 1984). They have criticized past research on cognition because it has tended to focus on individual mental activity without sufficient attention to the wider social and physical context in which any task or problem is embedded. This is, of course, analogous to the criticisms levied against schooling practices, which emphasize didactic instruction and individual performance and assessment in a very specialized setting. It is not quite accurate to speak of school instruction as consisting of disembodied or decontextualized tasks, problems, or learning. Rather, it takes place in a context that does not model any situation most learners are likely to face in the future. As Brown et al. (1989) say,

> Students need much more than abstract concepts and self-contained examples. They need to be exposed to the use of a domain's conceptual tools in authentic activity—to teachers acting as practitioners and using these tools in wrestling with problems of the world. . . . Classroom tasks . . . can completely fail to provide the contextual features that allow authentic activity. At the same time, students may come to rely, in important but little noticed ways, on features of the classroom context, in which the task is now embedded, that are wholly absent from and alien to authentic activity. Thus, much of what is learned in school may apply only to the ersatz activity, if it was learned through such activity. (p. 34)

Similarly, research on cognition and problem solving needs to consider the real life context—both the social and the physical setting—as part of the problem situation rather than as a set of variables to be controlled. Thus, Morris and Rouse (1985, p. 506), in an extensive review of research on troubleshooting and problem solving in electronics, criticize the research because most of the problems presented to trainees, even though they involved a variety of media (paper-and-pencil tasks, computer-based simulation, and occasionally even hardware), were generic or context-free and not intended to be part of any real system. As a result, these authors consider the research findings of little help in understanding actual performance.

In contrast, researchers using the tools of sociology and anthropology have examined how people acquire expertise in addressing such tasks as doing sales arithmetic (discussed earlier), performing a variety of jobs related to the distribution of milk products, and troubleshooting ill-defined problems in servicing photocopying machines (both described in greater detail below). Experts in any of these tasks do not call upon rote algorithms learned in school or proceed through routine checklists; rather, they call upon a range of clues provided by the environment, the practice and experience of their fellow workers, and their own situated knowledge to address the task at hand (deKleer & Brown, 1985; Orr, 1987a and b, 1988). Resnick (1987, p. 15) points out that this is true not only of workers in low skill occupations, but also of professionals in highly technical fields.

Scribner (1984) reflects this research when she speaks of using the environment as an active component of problem solving. She states:

> Skilled practical thinking incorporates features of the task environment (people, things, information) into the problem-solving system. It is as valid to describe the environment as part of the problem-solving system as it is to observe that problem-solving occurs "in" the environment. . . . The characteristic we claim for practical thinking goes beyond the contextualist position. It emphasizes the inextricability of task from environment, and the continual interplay between internal representations and operations and external reality throughout the course of the problem solving activity. (p. 23)

This view starts with the novice as one who has no specific knowledge of the particular work setting and who comes to the situation with everyday knowledge and general school learning. Novices become more expert as they become familiar with the setting (i.e., specific social, symbolic, technical, and material resources) and actively use it to complete assigned tasks with greater and greater success. Later steps in expertise are to invent more efficient problem solutions to share with others this learned problem solving expertise. Although this construction of expertise is based on current research, its key tenets fit well with the rationale for vocational education—learning through practical experience rather than through memorization of didactic knowledge.

To understand more fully the implications of considering the environment as part of any problem system facing an individual expert or novice, it is useful to distinguish among several components of such a system: other actors occupying various roles, the physical setting, explicit physical or conceptual tools, and the symbolic content. We discuss several of these in turn.

Socially Constructed Knowledge

Cognitive research conducted by scientists concerned with the social and cultural factors in learning conceive of all knowledge as being socially constructed, starting with language itself and ranging to the most technically sophisticated sorts of performance. The reading comprehension example described earlier (Palincsar & Brown, 1984), in which students construct the meaning of text passages collectively, illustrates how the use of social groups can make explicit covert cognitive processes involved in reading comprehension—a demonstration of effectively combining careful analysis of performance with the use of the social setting.

Another example concerns learning on the job rather than in the classroom. Orr (1987a and b, 1988, in press) studied how photocopier repair technicians go about diagnosing nonroutine problems and resolving them. By definition, these are problems that are not adequately covered in the cookbook procedures of the repair manuals furnished to the technicians. The presumption behind these procedures is that technicians do not need detailed machine knowledge, that all the knowledge that is necessary to the technician's job is embodied in the repair manuals and step-by-step routines. Yet, machines fail unpredictably and in ways that are not foreseen by prescribed repair schedules and directive procedures, forcing the technician to develop alternative channels of information.

At least two kinds of socially constructed knowledge enable the technicians to make effective repairs in such instances: their exchange of information with customers (e.g., what kind of use the machine gets, what other problems there have been, what preceded the breakdown, and how to avoid it in the future) and "war stories," anecdotes of experience shared among technicians. These stories are based on "... the community memory of the technicians, in which they preserve and circulate their hard won knowledge of machine arcana ... other technicians called for purposes of consultation will bring their own recollections to bear, and a good memory will make one a popular resource" (Orr, 1988, p. 4).

Although there is other information available to the technician—for example, the error logs created by the machine itself and the logbook containing records of installation, use, and previous service calls—Orr (1988) concludes that

> community memory is crucially important to the service task. Community memory preserves the working set of current knowledge, the information about new and as-yet-undocumented problems as well as critical information about the social labyrinths in which the machines are to be found. Service is indeed about the maintenance and repair of machines, at least partially so, but ... a substantial portion of the work observed could be better described as maintenance and repair of the social context in which the machine exists. (p. 1)

It is interesting to note that the telling of war stories is an aspect of their job that technicians appear to relish. Technicians will make it a point to meet for coffee or more extended meals when their work schedules allow and exchange anecdotes about unusual experiences with customers and machines. These stories almost never concern routine maintenance or problems that everyone knows how to fix. Orr (1987b) explains:

> New problems are interesting; technicians like new manifestations of the extremes of machine behavior or of human behavior with machines. Problems that require consideration of the chains of cause and effect in the machines and that shed new light on those chains are interesting to talk about. From the perspective of the community memory, it is necessary to talk about these problems to preserve and circulate the knowledge of how to solve them. . . . However, it is interest and involvement that cause the technicians to tell these stories. The stranger the sequence of events and interactions producing the machine behavior, the better the story is, and the more fun it is to tell. (p. 6)

What makes the war stories powerful is that they deal with machine and customer behavior within the context of a specific situation. In this regard, they not only provide new information that illuminates the workings of the machine but, also, specific applications of that information. The anecdotes amplify the technicians' community model of the machine and at the same time guide field work. According to Orr (1988), "[Another] virtue of anecdotes is their utility by persons of differing levels of expertise, with different understandings of the model; one expects novices to use the details of context more, having a less general model, while an expert would be more interested in the improvement of the model by the anecdote" (p. 8).

This modern example is an excellent illustration of the development of craft knowledge more commonly documented by anthropologists studying nonliterate cultures. Jordan (1989), after studying the failures of training in Western medicine provided to traditional birth attendants in Yucatan, draws the following contrasts between learning based on imitation and observation of the behaviors of more experienced practitioners and didactic teachings of abstract knowledge:

- Apprenticeship happens as a way of life, with almost no separation between daily activities and learning of professional skills.
- Activities are organized around the work that must be accomplished, with mastery appreciated for its immediate use and value rather than as a step toward a certificate or the next level of learning.
- The order of skill learning in apprenticeship tends to be from the periphery to the central activity, but it does not proceed in linear, chronologically ordered sequence predetermined by others.
- Performance lies in the doing of something rather than talking about it, talk being incidental to the activity.
- Evaluation of the learner's competence is implicit rather than explicit and externally imposed, effective performance being obvious to both master and apprentice.
- The master, unlike the teacher, is only a small source of the knowledge being learned; little identifiable teaching is going on.
- Stories are used to share experiences, enlarge the fund of knowledge available to the group, and legitimate members of the craft.

There is much to be learned from this characterization of apprenticeship. Which of these learning characteristics are immediately adaptable to today's world of work? Which are appropriate but would require major restructuring of both schooling and work? Which do not appear feasible or productive? Clearly, major adjustments will be needed, since all too many people appear to be without the skills to obtain jobs, let alone the ability to learn from the work situation in which they find themselves. The following discussion reports on research that throws some light on these questions.

From Transparency to Representation

One major problem with learning by doing in today's world is that much of the modern environment of many jobs as well as of ordinary life is made up of black boxes and/or "transparent" operations. The workings of the physical and social artifacts making up a given context are either impenetrable through everyday "common sense" or unobservable. This was not true in the preindustrial training of apprentices for various crafts, nor is it true of midwives in Yucatan or of some manufacturing workers in less developed countries today. An example would be the training of tailors, where every phase of garment production is quite explicit and easy to observe and can be imitated by the apprentice without detailed instruction (Lave, 1977).

The modern solution to the black box nature of physical artifacts is to provide detailed, preformulated instructions on operational or troubleshooting procedures (as with the technicians' manuals for photocopier repair) without attempting to gain an understanding of the artifact's context or its workings. The dangers of this approach, aside from its futility in the face of nonroutine occurrences, is illustrated by the events at Three Mile Island referred to above. In summarizing their research for the Air Force involving jet engine mechanics and avionics technicians, Lesgold et al. (1986) recommend ". . . more troubleshooting diagnosis practice, [and] practice in making diagnostic decisions, not just carrying out the physical steps dictated by someone else's decisions."

The presumption is that such practice will reveal a variety of problems, the resolution of which will engender a deeper understanding of the complex machine and its operation in context. Suchman (1986) states the proposition as follows: ". . . in the course of situated action, representation occurs when transparent activity becomes in some way problematic" (p. 50). In Orr's studies, for example, the workings of the machine and its use during normal operations are taken for granted and of little interest, that is, they are "transparent"—there is no particular reason to observe or think about them. The operations manual and routine procedures suffice for maintenance. It is only when something goes wrong that people need concern themselves with how the machine functions. It is at this point that the customer has to describe the nature of the malfunctioning (i.e., the customer's representation of the problem), thus helping the technician figure out what might be wrong (i.e., the technician's representation of the problem). Concludes Orr (1988): ". . . the art of diagnosis lies in producing the right pieces of information . . . creating a concise, coherent representation of the troubled situation such that it can be repaired and return to transparent [i.e., trouble-free] operation" (p. 6).

Use of Physical Setting and Tools

The photocopier technicians described by Orr construct problem representations on which they base their repairs from an environment made up of other humans and the machine itself. Suchman (1987) terms such action, based upon its material and social circumstances, "situated action":

> The basic premise is twofold: first, that what traditional behavioral sciences take to be cognitive phenomena have an essential relationship to a publicly available, collaboratively organized world of artifacts and actions, and secondly, that the significance of artifacts and actions, and the methods by which their significance is conveyed, have an essential relationship to their particular, concrete circumstances. (p. 50)

Observers find that ". . . setting and activity mutually create and change each other; in the process, 'problems' are generated and resolved" (Lave et al., 1984, p. 93).

Scribner's work (1986) is an example of relevant research in a modern occupational setting. She combines ethnographic and experimental techniques to elucidate the array of skills and knowledge acquired in the course of carrying out tasks required by particular jobs. Such skills include using situationally specific strategies, that is, using the setting and tools at hand to simplify the task so that least-effort activities will result in acceptable performance. In her studies of workers in a milk processing plant, Scribner investigated three different types of jobs and how people performed them: (1) assembling milk products, (2) pricing delivery tickets, and (3) taking inventory.

1. Product assemblers, classified as unskilled workers, were responsible for locating products stored in the warehouse and sending out to the loading platform the amount of each product ordered by drivers for their daily routes. Scribner found that assemblers departed from the literal format of the orders, filling identical case orders in a number of ways. Their procedures resulted in using the fewest physical moves per order, indicating that they used mental calculations and physical configurations to save themselves physical labor. The procedures were virtually error-free. When Scribner simulated this job using novices (ninth-graders), she found that they started out using literal strategies involving more physical labor, but acquired—

without instruction—some of the more obvious labor-saving strategies within a few days.

2. Wholesale delivery drivers were responsible for determining the cost of their daily deliveries to customers, using standard delivery tickets, preprinted with the customer's name and products usually purchased. Scribner found that the drivers solved pricing problems with identical structure in a variety of ways, departing from the multiplication algorithm when that simplified the arithmetic required, solving problems without the use of pencil and paper or calculators, and shifting back and forth in different base-number systems. In job simulations, drivers modulated their pricing techniques in accordance with the presence or absence of computational aids, and the procedures they used to solve the same problems changed under conditions of calculator use, paper-and-pencil arithmetic, or mental arithmetic. Solution procedures varied by individual as well as by problem and by calculating device. Novices, however, tended to solve all pricing problems by algorithmic procedures based on either unit prices or case prices. Interestingly, on a paper and pencil arithmetic test such as those administered in school, drivers, whose on-the-job accuracy was nearly perfect, made many errors on decimal multiplication problems similar in format to their pricing problems.

3. Inventory men were responsible for assessing the quantities of some one hundred products and accurately recording amounts on paper forms. They had a wide variety of strategies for determining case number, using combinatorial procedures that varied with array configurations which they mentally transformed in order to use multiplication short-cut methods of enumeration. Single cases were not used as the unit of count, although all counts were expressed on the completed inventory form in terms of case units.

Scribner argues that what appear to be very simple instances of practical thinking and problem solving emerge, when examined closely, "as an intricate and dynamic system organized by both factors in the world and subjective goals and knowledge" that is "simultaneously adaptive to ever-changing conditions in the world and to the purposes, values and knowledge of the person and the social group." Scribner discusses salient characteristics of skilled practical thinking but cautions that, although the characteristics are discussed individually, they are attributes of a system and as such they are "interrelated and implicate each other."

Conceptual Tools

Scribner's research has been described in some detail because it so clearly illustrates the nature of situated knowledge and action. More important for purposes of this paper, it documents the disjunctures between schooling and work discussed by Resnick (1987a)—that is, between the problem solving skills that workers acquire and use effectively on the job and what they have learned and can do in school. Here again, however, a caution is in order. The fact that people use the environment to solve mathematical problems more efficiently than through the use of school-learned algorithms does not negate the power of these algorithms. As computational requirements of a job increase beyond the chunking and pattern recognition capacities of an individual, problem solutions will of necessity have to draw on the type of declarative and procedural knowledge embodied in these algorithms and their use. Fortunately, Scribner and others are now extending their research to technically more complex jobs, so that they can document how people combine situation-derived knowledge with previously learned declarative and procedural knowledge to carry out their work.

It appears that performance in more "mental" occupations also requires the use of tools in context, which are knowledge tools employed by experts in specific domains. Brown et al. (1989) refer to the algorithms and principles of a particular field of knowledge as conceptual tools, available for use as a situation requires. As with all tools, however, conceptual tools are of little value unless people know when and how to use them. They note,

> It is quite possible to acquire a tool but to be unable to use it. Similarly, it is common for students to acquire algorithms, routines, and decontextualized definitions that they cannot use. . . . Students can often manipulate algorithms, routines, and definitions they have acquired with apparent competence and yet not reveal, to their teachers or themselves, that they would have no idea what to do if they came upon [a situation outside school that called for their application]. . . . People who use tools actively rather than just acquire them, by contrast, build an increasingly rich implicit understanding of the world in which they use the tools and of the tools themselves. The understanding, both of the world and of the tool, continually changes as a result of their interaction. Learning and acting are interestingly indistinct, learning being a continuous, life-long process resulting from acting in situations. (p. 33)

Induction into the Culture

The same authors point out that the use of a tool, whether physical or conceptual, is shaped not only by particular circumstance but also by the culture of its users, and these cultures vary from field to field. The subculture that characterizes a profession or line of work, be it that of midwives in Yucatan or mathematicians at MIT, shapes the behaviors and actions of its practitioners. Most often, these cultures are quite different from the culture of the classroom, even for highly academic fields. For instance, mathematics as taught in school generally is based on an authoritarian model of knowledge transmission, with mathematical knowledge seen as certain, absolute, and unchanging, and the doing of mathematics characterized as precise, disciplined, and leading to one correct answer (Mathematical Sciences Education Board, 1989). Mathematicians themselves, however, see mathematics as the science of patterns and the work of mathematicians as the search for patterns—in numerical data, in space, in science, in computers, and in other mathematical structures (e.g., numbers, geometric or algebraic structures, and linkages to other patterns) (Steen, 1988). This search entails pushing beyond the immediate answer, using alternative solution paths, and using short cuts that are appropriate to the situation, just as do the workers in the milk processing plant. To quote Brown et al. (1989) again,

> Learning how to use a tool involves far more than can be accounted for in any set of explicit rules. The occasions and conditions for use arise directly out of the context of activities of each community that uses the tool, framed by the way members of that community see the world. . . . Conceptual tools . . . reflect the cumulative wisdom of the culture in which they are used and the insights and experience of the individuals. Their meaning is not invariant but a product of negotiation within the community. . . . Activity, concept, and culture are interdependent. No one can be totally understood without the other two. Learning must involve all three. . . . To learn to use tools as practitioners use them, a student, like an apprentice, must enter that community and its culture. Thus, in a significant way, learning is, we believe, a process of enculturation. (p. 33)

Conceiving of occupations or professions as subcultures introduces yet another criticism of formal schooling, which is that schooling cannot authentically model their subcultures for students. Although students may be provided with the tools of a particular occupation (physical or conceptual), they are given little opportunity to engage in the real world tasks that characterize that particular occupation. Brown et al. put the case as follows:

> When authentic activities [i.e., the ordinary practices of an occupation or profession] are transferred to the classroom, their context is inevitably transmuted; they become classroom tasks and part of the school culture.

> Classroom procedures, as a result, are then applied to what have become classroom tasks. The system of learning and using (and, of course, testing) thereafter remains hermetically sealed within the self-confirming culture of the school. Consequently, contrary to the aim of schooling, success within this culture often has little bearing on performance elsewhere. (p. 34)

This echoes Resnick's comment that the methods and operation of formal schooling may in fact be antithetical to its goals.

Apprenticeship Models

All the notions discussed so far regarding successful performance and learning that is tied to successful performance—for example, the development of expertise, socially constructed knowledge, use of the environment to formulate and solve problems, and induction into the culture—point toward apprenticeship as a reasonable way of educating for work. Apprenticeship is socially and contextually situated and combines the learning of specialized and general skills. Yet, apprenticeship has been assumed to have fallen victim to the industrial revolution. Resnick (1987) argues this point when she states,

> In America, the story of the rise of vocational education in the skilled trades is simultaneously the story of the decline of apprenticeship. As the ideology of expanded schooling took hold and the nature of the workplace changed, we gave up opportunities for learning in the workplace in favor of school-based vocational education. School-like forms of instruction now dominate even in many "on-the-job" training programs. In the military, in community colleges, and in proprietary training institutes, the classroom culture often dominates, and difficulties frequently arise in the transition to actual job functioning. (p. 17)

As noted, the traditional apprenticeship model, if apprenticeships are to flourish again, needs transformation to match modern work. For example, the tailor apprentice described by Lave (1977) starts with pressing finished garments, a very low skill job, which implicitly demonstrates to him how garments are cut, the most technical part of tailoring. He also observes sewers and cutters as they do their work. Finally, he starts making garments on his own and begins to gain an understanding of quality criteria and the economic context in which he works as his garments are sold. The machinery used is inexpensive and easy to repair. By contrast, modern textile plants utilize sophisticated machines that are easy to operate, but whose expense makes it imperative that machine stoppage be avoided. Machine repair can no longer be a hit-or-miss affair learned through experience on the floor. The quality of the output is not readily discernable by the workers, as it was formerly, and jobs are less well defined. (See Bailey, 1988, for a detailed discussion of recent changes in the U.S. textile industry.) Obviously, most modern jobs, whether in manufacturing or in the service industries, whether in the private or public sector, do not have one of the attributes that made traditional craft apprenticeship so effective, namely the high visibility of the different skills needed to create a quality product or render an effective service. This would indicate that building in tutoring and error correction is critical to modern apprenticeships.

A Modern Example

The training of U.S. Navy quartermasters in charge of navigation, as described by Hutchins (in press), provides a cogent illustration. Navigation involves fixing the position of a ship at any given time and forecasting the ship's position at some specified time in the future, given its present (or some alternative) course. This complex activity has been decomposed into a series of tasks, ordered by complexity, through which the apprentice quartermaster moves in turn. Notes Hutchins: "The procedural decomposition of the task in this work configuration permits unskilled people to participate in complex activities" (p. 15). (Note that this decomposition is *procedure*-oriented rather than *skill*-oriented as in the traditional decomposition and teaching of skill hierarchies.) At each stage, the novice is monitored and guided, when necessary, by the person who has succeeded to the next stage and who has himself lived through the previous stage. The considerable overlap from stage to stage in the work performed and the built-in redundancy ensure effective apprenticeship. There are reasons for this careful overlapping of tasks: turnover in the Navy of seamen (and women) is very high, yet the task of navigating a large ship in constrained port facilities is a highly skilled operation which cannot be allowed to fail without disastrous consequences. Few modern work situations offer the careful induction and monitoring which this example illustrates, nor is it perhaps efficient in situations in which a novice might have more time available for learning the job and be faced with fewer immediately consequential opportunities for error. On the other hand, it is also true that very few work situations offer the opportunity for understanding the complex skills involved in such a clear manner.

Learning from Error

Seifert and Hutchins (1988) point out the advantages of learning from error which an apprenticeship provides: "Systems of cooperative work always rely on learning on the job, and where there is the need for learning, there is potential for error. . . ." This is particularly true in a work setting like the U.S. Navy, where changes in enlisted personnel occur with great frequency. Yet, the navigation system overall must be virtually error-free, even though by necessity it keeps replacing experienced personnel with new recruits. Thus, the cooperative work of the navigation team must, at one and the same time, try to avoid errors and take advantage of those that do occur, using them for training purposes so as to minimize future errors. Learning from errors requires explicit design: "In order to benefit from errors . . . [they] must be detected, diagnosed as to their cause, and corrected with useful feedback" (p. 4). This is facilitated in the navigation training system by the fact that the individuals detecting an error made by the novice have themselves been in the novice's position and understand the situation that gave rise to the error. The more experienced individuals of the team generally will have a good idea of why and how the novice went wrong and how to provide corrective feedback. In the process, both the learner and the tutor extend their knowledge of the overall system. It is the distribution of knowledge and overlapping responsibilities among team members that makes error detection, correction, and learning from error so effective. Seifert and Hutchins conclude that novices learn through error by being corrected by more experienced team members. They also learn to identify their own errors and the errors of others. This gives novices much greater opportunity for acquiring relevant knowledge:

> By participating in the process of error-based learning as a performer, an observer, and a teacher, the novice increases the number of learning experiences available for acquisition and deepens understanding of the lesson through interaction in several participatory roles. In addition, other learners provide models of the learning process itself, and this meta-knowledge may be helpful to novices in forming expectations about their own performance. (p.11)

Of course, the kind of apprenticeship system that builds learning from error into its training strategies comes at a cost. In navigation, the cost is overlap and redundancy—a cost deemed worth paying, given the turnover of personnel and the need for virtually error-free performance of the overall system at all times. By design, individuals not only experience and understand every phase of the complex cooperative task, but they are also expected to correct and guide less experienced members of the team. In most work situations, on the other hand, more skilled employees do not necessarily understand the responsibilities and specific subtasks of the less skilled workers who are also contributing to a common task. In the trade-off between attending to their own work and helping others with their learning, employees are rarely rewarded for the latter; more likely, they will be penalized for taking time away from their own tasks.

Apprenticeship in Professional Occupations

Brown et al. (1989) argue that apprenticeship is as relevant to highly "mental" domains as it is to the crafts and skilled technical fields. As individuals join a profession, apprenticeship helps them to take part in the activities of the experienced practitioners, observe their behaviors and interactions, and thus become inducted into the profession. The authors use the term "cognitive apprenticeship" in order to point out the central importance of situated activity in learning to know and learning to do and the dependence of such learning on appropriate contexts. They hold that this applies to learning to read, write, and do mathematics—learning generally associated with school (Collins, Brown, & Newman, in press)—as well as to learning one's profession. According to Brown et al., as individuals change their status from student to participant in a field of work, they must learn to

> recognize and resolve the ill-defined problems that issue out of authentic activity, in contrast to the well-defined exercises that are typically given to them in text books and on exams throughout their earlier schooling. It is at this stage, in short, that students no longer behave as students, but as practitioners, and develop their conceptual understanding through social interaction and collaboration in the culture of the domain, not of the school. . . . In essence, cognitive apprenticeship attempts to promote learning within the nexus of activity, tool, and culture. . . . If one agrees with the centrality of a form of apprenticeship for becoming an effective practitioner of any trade, craft, service, technical occupation, or profession, then the critical issue becomes one of providing the appropriate setting and human support to make effective apprenticeship possible. (p. 40)

Effective Apprenticeships

All the research summarized so far points to a cardinal principle: Training programs—whether in or out of school—need to focus upon providing opportunities for apprentice workers to experience as closely as possible real life working situations in which they can gain both practical and theoretical knowledge in their chosen trade or profession. Realistically, simulation programs are often required to replace real systems in order to provide this experience in situations where the actual context and equipment cannot be duplicated or where risks cannot be taken with the real system (e.g., nuclear power plants and aircraft pilot training).

Within the real life setting, apprentices need opportunities to address ill-defined problems, to construct meaningful problem-solution relationships, and to create multiple solutions. It is important to emphasize that an apprenticeship must be more than just a hands-on experience: Apprentices in modern work settings need opportunities to collaborate with highly skilled workers and teachers who can provide guidance and explanation as the situation warrants. Skilled coworkers can provide specific information, common sense understanding, and practical advice. As Sticht (1987) suggests, more formal teaching occasions can facilitate learning through direct instruction which is grounded in the specific problem solving situation faced by the apprentice.

As the problem solving skills of apprentices become more complex, there should be opportunities for skilled workers or teachers to collaborate with them on advancing everyone's job-related knowledge, expert and novice alike. Personal and shared practice can be discussed and legitimized, and new procedures can be invented. Apprentices can be encouraged to use their creativity and ingenuity to theorize about the nature of the problems they face in their jobs and about the application of their knowledge to future problem solving situations.

Brown et al. (1989, p. 40) stress the importance of collaborative learning to their conception of effective apprenticeship, since working in groups promotes the social interaction they consider necessary to authentic induction into a trade or profession. For one thing, working in groups encourages the collective solving of problems, which not only draws on the individual knowledge of all the group members (including the apprentice's), but also allows the apprentice to participate in developing new insights and solutions that are the product of the group as a whole. Second, group work allows novices to observe and understand the tasks and responsibilities of the more experienced group members, discuss these different roles, and perhaps even try out some of them. Third, more experienced members of the group can help the apprentice to confront ineffective strategies and misconceptions, as demonstrated in the navigation example. Particularly if the quality of the product or service of the group as a whole is adversely affected by a novice's errors, groups can be very effective in drawing out, confronting, and correcting inappropriate responses, misunderstandings, and ineffective strategies. And fourth, apprentices working in groups made up of a variety of expertise and responsibilities will acquire collaborative work skills, which are needed more and more in the workplace. There are very few work situations that do not involve people learning and working in conjunction with others; hence, becoming proficient in the requisite social skills is as important as becoming expert in the practical and theoretical knowledge skills. Effective apprenticeship promotes all three.

Simulations

Two points have been made about differences between traditional and modern apprenticeship: First, the nature of most jobs does not allow a novice, merely through observation, to acquire awareness of what the expert actually does or why. Because various individual and group tasks lack any explanatory context for why various operations are engaged in, there is little to be learned by simply being on the scene. Often the technology is so complex, arcane, hidden, or automated (like the electronics of the photocopier), that the technician dealing with it, even if expert, is not expected to understand it, much less explain it to someone else. Second, despite the need for explanation and guidance to induct less experienced practitioners, most work situations rarely allow the more expert workers to take time from their own tasks to make their procedures and problem solving paradigms explicit. Only when necessary to their own performance is this encouraged, as in the photocopier-repair or navigation examples.

One response to the distance between school learning and effective job performance and the difficulties of creating apprenticeships that advance the requisite competencies is the simulation of appropriate instructional situations through computer programs. This line of research, which focuses on careful analyses of tasks and functions that characterize effective performance, has led to several training models. Gott (1988) discusses two such models and several training programs based on them such as procedures-based training and device knowledge-based training. Both models are based on providing to learners ". . . better content (through cognitive models) and better method (principally through progressive and supported practice)" (p. 101).

Procedures-Based Training

When tasks are of a nature that makes them difficult to understand or to learn through observation and practice, an alternative is to analyze the procedures being followed and represent them as a rule-based system that can be followed and learned by the apprentice. The results may be a step-by-step training program, a technician's manual that is based on an "ideal" systems model and is highly prescriptive, or an equally directive and inflexible computer program simulating practical performance. There has been some success with such programs in well-structured domains that are amenable to rule-based procedures. Goals are made explicit; procedural steps are grouped in logical order; and corrective feedback and tutoring is provided as errors are made or anticipated. There are, however, severe limits in the types of problems that can be addressed. As Orr's photocopier repair anecdotes illustrate, when conditions are altered from what the repair manual or training program anticipates, these become useless, no matter how good their logic. Concludes Gott (1988):

> The instructional approach that follows from deterministic performance models is . . . limited to the initial stages of learning and the easier problems. As problems become more complex . . . situation-specific algorithms become less feasible, and experts demonstrate more interplay between procedural rules and other knowledge components. . . . [T]he robust performance is one in which procedural steps are not just naked rule-based actions but instead supported by explanations. . . . [T]he performer not only knows the procedural steps for task execution but also understands when to deploy them and why they work. (p. 120)

Device Knowledge-Based Training

A reasonable assumption is that skilled performers have greater knowledge about the devices and systems with which they work than do apprentices. It is this very knowledge of how things work that allows them to understand the prescribed procedures, know when they are effective and when not (strategic or control knowledge), and invent new ones when necessary. It is less clear how such knowledge can be taught most effectively, that is, made explicit, for task performance that is unobservable to the apprentice.

The electronics technicians program discussed in Sticht (1987) and Sticht et al. (1987) represents an attempt to use simple electric devices (e.g., flashlights, table lamps, AC adapters) to teach knowledge of devices to low-aptitude students. Gott describes several computer simulation programs that represent various pedagogical strategies designed to teach device or systems knowledge. Her review leads her to suggest that the greatest promise lies in programs that coordinate device, procedural, and strategic knowledge from the outset, even as the training moves from simple to more complex problems. Such an integrated problem solving approach comes closest to modeling classic apprenticeship methods for the many modern day tasks that involve tacit (unobservable) knowledge, processes, and their effective application in specific situations.

HOW TO REFORM VOCATIONAL EDUCATION

Before considering what changes need to be made in current vocational education programs, it may be useful to summarize research findings reviewed in this paper concerning effective workers and effective education for the modern workplace.

Summary of Findings

Characteristics of Effective Workers

Based upon studies of expertise, Taylor (1989) has characterized effective workers as follows:

1. Effective workers simplify the task, using short cuts and developing least-effort strategies.
2. When necessary, effective workers redefine externally defined problems into personally constituted problems. They are able to differentiate between routine problems that require nothing more than the application of set procedures and problems that require (or become more tractable through) redefinition.
3. Effective workers use flexible strategies as they depart from the literal framework and reorganize the assigned task to "fit" with the available social, symbolic, technical, and material resources at their disposal.
4. Effective workers develop tentative "gap-closing" or intermediate solutions.
5. Effective workers collaborate to develop situated explanations, examine contradictions, explore procedural possibilities, and discuss alternative solutions.
6. Effective workers produce accurate task completion solutions.
7. Effective workers continue to develop competence.

Experts in a field display specificity of knowledge schemata and procedural and goal-oriented knowledge as well as the ability to perceive large meaningful patterns. They also make use of generalized thinking and problem solving skills which they put into play when specialized knowledge no longer suffices (Glaser, 1987a; Nickerson, 1988). Experts also engage in such self-regulatory processes as planning their work, evaluating alternative solutions, checking their performance, and explaining discrepancies between planned and actual performance. In other words, they engage in the kind of higher-order thinking described by Resnick (1987b)—nonalgorithmic (not fully specified ahead of time), complex (solution paths are not fully visible), sometimes yielding multiple solutions with offsetting advantages and disadvantages, requiring nuanced judgment and interpretation, involving uncertainty and the application of multiple criteria, and requiring self-regulation and effort.

Moreover, competent individuals are not dependent solely on the knowledge inside their own heads. They use the environment (made up of both physical and human resources) to reformulate and accomplish their tasks. Working in groups, they often construct knowledge together that advances the communal task and makes the group and the individuals within it more proficient.

Becoming an Effective Worker

This paper has reviewed educational strategies for preparing for work that arise from three different traditions: the investigations of cognitive psychologists concerned with the individual learner, the investigations of sociologists and anthropologists observing people's problem solving behaviors at work and in other real life settings, and considerations of modern counterparts to traditional craft apprenticeship. Though they have been discussed separately, these three approaches give rise to some common findings on what constitutes work competence and how learners develop it.

Glaser and Bassok (1989) recently summarized the accomplishments of cognitive research over the last twenty-five years, particularly as it relates to instruction. They point out that much of the work has focused on three areas: the analysis of competence, which has received by far the most attention; the learner's initial state of knowledge and skills, which has become a more active area of research recently; and the processes by which learners move from their initial state to a state of competency, an area still underdeveloped.

The investigations based on *analyses of competence*, including the identification of differences between novices and experts, have made possible the formal modeling and simulation of complex cognitive performance, leading to a number of successful education and training programs. A major finding is that *it is not sufficient to teach knowledge and procedures; instruction must also focus on conditions of application of the knowledge and skills being learned.*

Another aspect of this work has been concerned with the organization and structure of knowledge in an individual's head. The debate among cognitive psychologists as to the importance of domain-specific knowledge versus generalizable skills is being resolved through better recognition of the role of each (Nickerson, 1988). It appears that the process of becoming an expert is not linear and, for most occupations or professions, cannot be divided up into a number of discrete skills that can be taught in isolation. Researchers interested in the acquisition of expertise are developing courses that weave together specific declarative and procedural knowledge with the development of general basic skills and problem solving strategies. Theories of learning are being constructed to accommodate the importance of domain specificity and yet take advantage of the utility of generalizable as well as metacognitive, self-regulatory skills. Perkins and Salomon (1989) put the case as follows: "Although we don't want the weak results of the kind of attention to general heuristics that neglects knowledge base, we also don't want the brittle competency forged by exclusive attention to particularized knowledge" (pp. 23-24). Current research indicates that *instruction must intermingle context specificity and generality, including the development of self-regulatory skills and performance control strategies.*

Research on what *knowledge and skills the learner brings to instruction* has focused on mathematics and, even more so, on science learning. This research has provided new insight as to what makes instruction effective. Instead of constructing curriculum top-down by encoding the knowledge of experts in suitably simplified materials, *instruction should take into account the learner's original ideas, stage discrepant or confirming experiences to stimulate questions, and encourage the generation of a range of responses with the opportunity to apply these in various situations.*

Researchers concerned with how people actually move from their *initial state of knowledge and skills to effective performance* in work settings are uncovering the importance of situated learning and learning in context. This includes the use of the physical environment and the tools it provides to represent problems and develop solutions; the cooperative construction of knowledge among groups of workers doing common or related tasks; and the importance of becoming part of the community that shares a particular domain of knowledge, set of skills, and/or method of representing and resolving problems.

These streams of cognitive research come together in the current renewed interest in learning through apprenticeship. A number of researchers have tried to develop counterparts to the traditional apprenticeship, designing courses or computer simulations that incorporate engagement with the "stuff" (physical, mental, and social) of a task. They also set it in context, provide diagnosis and correction of initial misconceptions, and give tutoring structured to fit the learner's level of competence. The research on experts and novices has resulted in greater attention to the several types of knowledge (and their structure and interrelationships) that competent individuals display. The research on situated learning and socially constructed knowledge highlights the need for providing a real world context (both physical and social) for education and training intended to prepare learners for work. An optimal educational response melding these requirements would appear to be modern forms of apprenticeships in environments that make task knowledge and problem solving procedures explicit and that provide for feedback and tutoring by more experienced coworkers.

In short,

- The usual decomposition and decontextualized teaching of skill hierarchies is seldom effective in educating and training for work. In contrast, the analysis and distribution of complex tasks to allow shared performance (or its simulated counterpart) by less experienced and more experienced workers provides a highly effective learning situation.

- Thus, people build workplace expertise through the opportunity to participate, under the tutelage and mentorship of experts, in physical and intellectual tasks specific to a particular work setting.

- This situated learning enables them to use the social, symbolic, technological, and material resources provided by the work context to structure problems and problem solutions.

- The symbol manipulation and abstract thinking skills required in many technical jobs today are learned effectively through a combination of practice and explicit teaching in a meaningful context.

- The process of progressing from novice to expert takes time as individuals achieve increasing levels of understanding—of knowledge, procedures, strategies, and social interactions relevant to their work and of the subculture of the occupation or profession.

Issues That Must Be Addressed

What are the present-day impediments to providing the opportunity to participate in meaningful work experience or effective simulations? Several have been discussed in some detail earlier in this paper:

1. The increasing emphasis on school-based, formal education, both in school and even in out-of-school training, which has supplanted practical experience as a recognized learning situation. Resnick (1987) points out that this is as true of professional education as it is for job training. This shift has led to an artificial separation between knowledge (knowing what) and practice (knowing how and when) and a mismatch between the culture of the school and the culture of the workplace.

2. The current insistence on sequential learning of skill hierarchies and especially the basics—literacy and numeracy skills, fundamentals of the discipline(s) underlying a particular set of tasks, and general reasoning skills—without application to practice in context. This pedagogic approach has resulted from premature application of incomplete research understandings and is contradicted by current research evidence.

3. The increasing technological and intellectual complexities of the modern workplace make craft-style apprenticeship—largely based on observation, peripheral participation, and self-correction—ineffective. In many settings, the response has been to replace worker competency and in-depth knowledge with turn-key operations that disconnect workers from their tasks and exclude them from meaning-oriented problem solving. Instead, the declarative, procedural, strategic, and social knowledge used by the expert needs to be made explicit, so that novices can develop increasingly sophisticated problem and task representations.

4. The organization and reward structure of work, which for the most part does not recognize the importance of tutoring and mentoring less experienced workers. Not only do the knowledge, procedures, and decision rules of the more experienced individuals have to be made explicit, these individuals also need to be assigned specific responsibility for diagnosing and correcting the novices' errors and guiding them to achieve greater proficiency. The reward structure within the workplace needs to recognize the contribution made by the experts as they help their less experienced colleagues move up the ladder.

5. A fifth impediment which highlights important structural difficulties in the present-day organization of vocational education is *the common failure to provide the requisite work-linked education and training where individuals can take advantage of them.* Kirst (personal communication, November 17, 1988) cogently made this point in his comments on California's attempt to provide good workplace simulations in vocational training programs. Ten years ago, the California Vocational Education Board came up with a new vision: regional centers that would provide realistic work settings—recreating assembly lines; technically and mechanically accurate production facilities; electronics plant conditions; settings for food and other service occupations; and the like. These centers are in existence now and several of them are show places with excellent staff who know what they are doing. The problem is that, for the most part, the students are not there. The whole vision has been jeopardized by the logistics such as the difficulty in transporting individual students from different locations to the centers and the dilemma of fitting their practical training at the centers into their regular school schedules.

The difficulties experienced by the California students with the regional centers are reminiscent of the difficulties of a set of urban families studied by Taylor and Dorsey-Gaines (1988). These families live below the poverty level in an economically depressed, inner-city neighborhood that leaves them isolated and bereft of essential services and employment opportunities. Jerry, one of the fathers in the study, had to take two buses every morning to travel the few miles to the silk screening factory where he worked. The journey took two hours, and he began work at 7:30 a.m. Similarly, Pauline attended a community college where she studied computer programming, but when she finished her first year of study and tried to obtain summer employment, she found that there were no jobs available within reach by public transportation.

However difficult the task may seem, the lives of youths in and out of school and the circumstances of their lives—inadequate housing, the lack of essential services, attendance at poor schools, if at all, with limited opportunities either for higher education or for productive jobs with advancement potential—must be part of the design of effective training and work experience opportunities. No matter how good a program is, unless it is located in a place that is easily accessible and fulfills some specific need of the working community, the program will fail.

Some Approaches

What needs to be done seems clear enough:

- Integrate learning of basic skills with learning about the devices, systems, procedures, decision rules, and social interactions characteristic of specific work settings and responsibilities;
- Provide most education for work in settings that are or duplicate as closely as possible the work setting for which the individual is preparing, while ensuring that the necessary guidance and tutoring is provided;
- Ensure that the education being provided is not narrowly limiting in its scope; and
- Take into account the personal lives of the student or novice worker and recognize the interrelationships that exist between healthy families, schools that educate, and productive workplaces.

The hard task is to design programs that will meet these conditions, given today's organization of schools and work. It is not accidental that several of the illustrations of successful training provided earlier are drawn from the military, which operates under different conditions from the civilian sector. Young people, once they have entered the service, are committed to staying there for the period of their enlistment. Instruction is judged by how well the trainees perform the jobs for which they were trained, and the quality of the job performance is usually self-evident. None of these characteristics is common to either school or work.

One suggestion for reform that is frequently made is to *expand and upgrade apprenticeship opportunities*. The William T. Grant Foundation on Work, Family, and Citizenship (1988) puts the case as follows:

> The gulf between vocational education in American secondary schools (particularly urban high schools) and the realities of employment in high-paying craft occupations is wide and possibly widening. Yet, this gap is significantly narrower in West Germany, Switzerland, and Austria. There, apprenticeships cover almost all occupations requiring high-level skills and employers participate willingly in training costs as a regular part of their employee recruitment efforts. Apprenticeship programs assist young people in the 15-19-year age group with an almost seamless passage from secondary classrooms through a combination of academic work and on-the-job training and on into full membership in trades demanding highly specialized skills. West Germany's apprenticeship system enrolls over half of all 15-18-year-olds, and those of Austria and Switzerland number one third of their noncollege youth. Students are well trained and highly motivated, and

almost all get good jobs or continue their education upon completion of the apprenticeships. (pp. 100-101)

The Commission goes on to note that, altogether, only fifteen hundred students are enrolled in the school-to-work apprenticeship programs offered in American high schools, and that only five percent of high school graduates are in apprenticeships the year following graduation and only one percent at the three-year mark. They urge that federal and state agencies together with employers, "develop a modern and more responsive American approach to training through apprenticeship."

Not all analysts would agree. Chipman (1989) considers the return to an apprenticeship form of education on any large scale a romantic and infeasible notion. She urges instead that school instruction incorporate what researchers have uncovered about the virtues of formal and informal learning. Indeed, France appears to be abandoning its apprenticeship training system and the German-speaking countries are infusing their programs with increasing amounts of academic instruction. Moreover, practices that work in other countries are not always readily transferrable to the United States due to the differences in its socialized workforce and management styles.

Nevertheless, there is every reason to give the Grant Foundation's proposal serious consideration. At the very least, more experimentation is needed to ascertain to what extent effective apprenticeships can be set up in a variety of working situations and how learning environments, in and out of school, might be created to integrate different levels of theoretical and practical learning. Also, practitioners in some schools have found through experience what works in vocational education. Such naturally occurring experiments should be identified and carefully described with their outcomes evaluated.

A second suggestion, in line with the expansion of apprenticeships and other forms of on-the-job education, is to *free students from compulsory full-time school attendance after age 16, and perhaps as early as age 14.*

Students should have the option of entering the productive workforce earlier than at age 18, spending a half day in school and a half day working (Resnick, personal communication, December 2, 1988). For students choosing this option, in-school time should not focus on education for work, which would be provided through direct experience, but on symbolic learning that extends the power of what is learned on the job and on education for citizenship. By the same token, the work experiences must be designed to allow students to engage in meaningful tasks under the tutelage of experienced workers so that they can grow in responsibility and expertise.

One important objection to this early induction into apprenticeships and the world of work is that it resembles the old-style German trade-school model which virtually foreclosed any possibility of moving from one trade into another or into a more promising occupation. Such a limiting view of education is antithetical to the American conception of equality of educational opportunity.

It is important, therefore, to *ensure that apprenticeships and other work experiences teach* not only how to do a particular job or task but also *how to become a competent novice*, able to learn from any work setting.

Being a competent novice means learning how to manage oneself effectively in a novel situation by noticing procedures and social interactions, copying experts, asking for explanations and guidance, getting a mentor, and taking extra time (outside official work hours) to study the layout, devices, tools, and other artifacts (physical and symbolic) that make up the work setting. These are not behaviors encouraged in formal classrooms; extracurricular activities are more likely sites for learning the quasi-social skills that characterize a competent novice. If industry and business were organized to allow that kind of learning through work experience, opportunities for changing occupations would be opened up since these general skills are germane to any new job. However, that is a very big if, indeed. Much of the work experience open to teenagers today consists of dead-end jobs entailing low level skills quickly learned and minimally transferrable to other settings. Vaughan and Berryman (1989) find that U.S. businesses put fewer of their training dollars into the less educated, the lower skilled, or the occupations that these individuals tend to hold.

If the workplace is most effective—if not always structured—for situated learning of work-related knowledge (cognitive models of tasks and devices) and work-related skills (procedural, social, and cultural), and academic schooling is most effective for the learning of more general, symbolic, and cultural knowledge, then what is the role of vocational education? Can work experience be adequately modeled in the school setting? Probably less and less so as work tasks become more complex. The knowledge and skills needed for competent performance grow increasingly tacit and unobservable to nonexperts (including school teachers who are not part of the relevant occupation or profession), and jobs are tied more and more to highly sophisticated technology not available to schools. Even the project approach, say, building or rehabilitating a house, does not really model operating conditions, constraints, criteria for evaluating and rewarding performance, or social relationships in the relevant trades. Moreover, while the project method can be a fertile setting for learning, it requires highly skilled teachers—rare in any field—to take full advantage of this opportunity. More often, the project method either results in a form of disguised chaos, in which students learn little about the "what" and less about the "why" of what they are doing, or it simply replicates in another form the didactic teaching of the academic classroom.

Indeed, the Committee for Economic Development (1985) has charged,

> Many "vocational education" programs are almost worthless. They are a cruel hoax on young people looking to acquire marketable skills. So many different and, in many cases, unproductive programs in our public schools have been called "vocational education" that most existing programs need to be disbanded and reshaped.

A good bit is known about what that reshaping needs to include. There are urban high schools which are effective in preparing students both for an occupation and for further study, if the students so choose. Mitchell, Russell, & Benson (1989) studied nine such schools or school programs. They found that these exemplary schools were characterized by some of the same general attributes that make any urban high school effective: a safe and orderly environment, a businesslike attitude among students and teachers, a warm and caring school climate, and high expectations for the students. Additionally, the successful schools *forge strong linkages with business and industry, which permits them to organize curricula around an industry and integrate theory and practice.*

These schools have learned how to create a context in which students can succeed. According to Mitchell et al. (1989), graduates ". . . have a range of choices for life after high school: four-year college, professional institutes, two-year college, a job with career prospects, or a combination of college and work" (p. 107). The authors comment that, because of their very success, these exemplary schools are short-changed in the allocation of monies available for vocational education, surely a perverse incentive system for building programs and schools that work. Apparently, not only must curricula and instruction be changed in most vocational programs, but so must policies that currently govern them.

It is obvious that settings that are effective in educating for work *erase the artificial boundaries between different forms of preparation*. The old distinctions among occupations—trades and professions, blue-collar and white-collar, which ones require vocational preparation, and which ones professional preparation—are rapidly becoming obsolete in the modern workplace. The distinction between vocational education and on-the-job training is equally untenable in light of what is now known about how people become competent workers. This is also true of the distinction between academic learning, vocational education, and learning through practice. Both school and work must be restructured so as to allow the modeling of authentic work experience during formal schooling and to allow the opportunity for education at work. This will be no easy task. McDonnell (1989) points out that any restructuring of schools has profound implications for use of resources and realignment of authority relationships and will meet with covert, if not overt, resistance. Restructuring of business to make possible effective learning by novice workers through expansion of modern-day apprenticeships which combine theoretical and practical learning will be, if anything, even harder to accomplish. And school-business linkages that yield results for students will be the hardest of all to establish, entailing deep changes in the largely incompatible cultures and incentive structures of two entrenched worlds, that of school and that of work. Yet the country can no longer afford a bifurcated labor force, with an increasing proportion of individuals underskilled and unable to obtain or transition to jobs of any complexity. Both the economic and the social costs are too high, for the individual and for the country. The careful analyses of performance and the research of the transition to competency and expertise reviewed in this paper must be extended into many more sectors. As understanding of successful formal and informal education grows, training models and programs based on the findings need to be developed for use in schools, during apprenticeships, and for older workers as skill demands change.

One final point deserves reemphasizing: *The organization of opportunities for education for work must be compatible with the social organization of an individual's or group's everyday life.*

This is equally true of students still in school and of apprentice workers. Matters of scheduling, use of time and space, availability of transportation, responsibilities outside of school or work, and special individual or group attributes must dictate the design of programs and work opportunities. Surely, this can be accomplished if American society cares deeply enough about the development of its greatest asset, its young people.

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