CONTEXTUAL KNOWLEDGE
AND THE DIFFUSION OF TECHNOLOGY
IN CONSTRUCTION

by

Ann Margaret Brach

S.M. Civil Engineering, Massachusetts Institute of Technology
(1987)

B.S. Civil Engineering, Northeastern University
(1985)

Submitted to the Department of
Civil Engineering in Partial Fulfillment of
the Requirements for the Degree of

DOCTOR OF PHILOSOPHY
in Civil Engineering

at the

Massachusetts Institute of Technology

June 1991

© Massachusetts Institute of Technology 1991
All rights reserved

Signature of Author

Department of Civil Engineering
May 23, 1991

Certified by

Fred Moavenzadeh
Director, Center for Construction Research and Education
Thesis Supervisor

Accepted by

Ole S. Madsen
Departmental Committee on Graduate Studies
CONTEXTUAL KNOWLEDGE
AND THE DIFFUSION OF TECHNOLOGY
IN CONSTRUCTION

by

Ann Margaret Brach

ABSTRACT

The U.S. construction industry as a whole is not commonly viewed as a very technologically innovative industry. Yet a wide range of technologies is required for this industry to carry out its function, which often involves solving challenging problems in unique projects (harsh environments, etc.) Despite the importance of technology, construction does not engage in firm-sponsored R&D nor do many companies actively purchase new technologies or hire persons with advanced degrees in technological and scientific specialties. Nevertheless, construction firms do manage to procure innovative technologies when they are required for projects.

The central argument of this thesis is that the behavior of the construction industry in matters related to technology—learning about, acquiring and developing technology—is a consequence of the strong role of “contextual knowledge” in the industry. Contextual knowledge is knowledge linked to the context in which it is gained rather than known formally, abstracted from its context. Dependence on knowledge which remains closely linked with the context in which it is gained results in patterns of behavior which will differ from industries and activities which draw from formal or context-independent knowledge.

In this research a conceptual framework of contextual knowledge in construction is developed and its effect on construction’s technology-related behavior is explored using a case study method. It is found that technology-related behaviors are largely dependent on the context (the construction project) in which the technology is or will be used. This pattern is most applicable in the development of process technology or construction technique. It is also most accurately descriptive of the general contractor although such context-oriented behavior is also found in other participants such as the designer or the specialty contractor.

Thesis Supervisor: Dr. Fred Moavenzadeh
Acknowledgements

To my committee, Profs. Marks and von Hippel, for their advice and support, and especially my committee chairman, Prof. Moavenzadeh, for believing beyond all hope that among all my random ideas one might actually evolve into a thesis topic.

To all of my friends here at M.I.T. and at Bayridge Residence, for helping me keep things in perspective – and for listening to all my theories.

To all those who generously gave of their time to help me find projects to study and to allow me to interview them.

To my parents, for not needing this thesis.
# TABLE OF CONTENTS

TITLE PAGE ...................................................... 1
ABSTRACT .......................................................... 2
ACKNOWLEDGEMENTS ........................................... 3
TABLE OF CONTENTS ............................................. 4
LIST OF FIGURES AND TABLE ................................... 7

**CHAPTER I: INTRODUCTION** ................................ 8

Description of the general problem ......................... 8
Thesis ............................................................. 11

**CHAPTER II: FORMAL KNOWLEDGE AND CONTEXTUAL KNOWLEDGE** .... 13

Formal vs contextual knowledge ............................. 13
Conceptual background ........................................ 17
Technology development and contextual knowledge related research ........................................... 21
Technological development in the construction industry ............................................................. 27

**CHAPTER III: METHODOLOGY** ................................ 35

The importance of context and therefore of the project ................................................................. 35
Description of method followed ............................. 36
Case study of a construction firm .......................... 36
Pilot study .......................................................... 39
Second and third case studies ............................... 44

**CHAPTER IV: CASE STUDY OF CONSTRUCTION FIRM** ........... 47

Results of interview ............................................ 47
Technological development on a project basis .......... 51
A power plant ..................................................... 51
An energy conversion project ................................ 52
A bridge rehabilitation project ............................. 54
Analysis of all five case studies ........................... 57
Conclusions ......................................................... 63

**CHAPTER V: POST OFFICE SQUARE PARKING GARAGE** ........ 67

Case studies for the thesis research ....................... 67
Description of Post Office Square project ................. 68
CHAPTER VI: NORTH STATION TRANSPORTATION IMPROVEMENTS PROJECT AND JAMESTOWN VERRAZANO BRIDGE

Description of North Station and Jamestown Bridge projects ........................................ 117
Major technologies ........................................ 120
Polymer slurry ........................................ 120
Concrete forming system ........................................ 124
Super low ground pressure (SLGP) equipment ........................................ 125
Precast segmental construction ........................................ 126
Results of North Station and Jamestown Verrazano Bridge Case Studies .......................... 128
Communication ........................................ 128
Communication in the industry in general ........................................ 128
Communication within firms ........................................ 132
Visual presentation of information ........................................ 133
Experience ........................................ 134
Role of the Project ........................................ 137
Project as classroom ........................................ 137
Project as laboratory ........................................ 138
Importance of Process ........................................ 142
Role of Participants in Project ........................................ 143
Owner ........................................ 143
Designer ........................................ 144
Consultants/Advisors ........................................ 145
CHAPTER VII: THE ROLE OF CONTEXTUAL KNOWLEDGE IN CONSTRUCTION

Introduction..................................159
Description of conceptual framework........159
  Project-orientedness of construction........161
  Fragmentation of knowledge in construction..163
    Learning about the construction process
    itself......................................164
    Learning about and acquiring technology...167
    Improving or developing technology........169
An economic explanation........................176
  Sources of innovation........................177
  Informal know-how trading..................181
Conclusion..................................184

CHAPTER VIII: CONCLUSION.........................186

Benefits of conceptual framework..........186
  Management of Technology..................186
  Research and Education....................191
  How broadly the conceptual framework might
  be applied outside of construction........197
Future research................................199
Summary.....................................201

REFERENCES..................................204

APPENDIX....................................209
LIST OF FIGURES AND TABLE

Figure 1  Flow of Information in Science and Technology ...24
Figure 2  Flow of Information in Technology, modified .....28
Figure 3  Up/down Construction Process: Major Subsystems ........................................71
Figure 4  Conceptual Framework: the Role of Contextual Knowledge in Construction ..................162

Table  Cost Comparison of Bentonite Slurry and Polymer Slurry ........................................122
Chapter I

INTRODUCTION

Description of the general problem

The U.S. construction industry as a whole is not commonly viewed as a very technologically innovative industry. It exhibits an apparent slowness to develop or incorporate new technologies. Very little formal research and development is carried out by the industry: in 1987 the Office of Technology Assessment estimated R&D at 0.33% of the value of construction (OTA). For some years there have also been reports of declining productivity in the domestic construction industry and declining international competitiveness.

The advent of new technologies in the areas of materials, robotics and computers and information has promised to revolutionize many industries, not least among
these construction. Research that seeks to incorporate these advanced technologies into construction is ongoing in many universities and research laboratories. In addition to this scientific and technological R&D, members of industry, academia and government have suggested several possible mechanisms for successfully introducing actual products based on this R&D into the construction process. These mechanisms include encouraging innovation in supplying industries, pilot use of riskier innovations on military or government projects and creation of incentives for construction firms themselves to innovate.

While such efforts are valuable and will undoubtedly be very helpful in certain sectors of the industry or with certain technologies, they reflect a particular approach to R&D and innovation, one which may not be ideal for all sectors or technologies. This approach is derived from the ways that technology is developed in the more R&D-intensive industries.

Certain industries tend to form the standard for judging research and development and technological innovation. These include aerospace, automotive, electronics, as well as biomedical, chemical and certain materials industries. Construction differs from these industries in a fundamental way. This difference involves the types of knowledge more heavily relied upon in the two types of industries.
Knowledge of the construction process is largely intuitive and practical, derived from personal experience. Construction relies heavily on a holistic, often unanalyzed, knowledge which is integrated into the experienced person. It is "holistic" or "synthetic" because it is a knowledge of the various parts of the construction process as they are combined in specific projects. Thus it is a knowledge of context or "contextual" knowledge. In contrast, the other industries mentioned above rely on a more formal knowledge of their processes, a knowledge that abstracts the fundamental elements and relationships from a multitude of specific and very diverse instances, in other words, knowledge which is independent of context. These two kinds of knowledge, formal and contextual, are explained in more detail in Chapter II.

Despite the fact that construction does not follow the model of the other industries mentioned, innovation does occur. How it occurs may very well differ among construction sectors. Each sector of the construction industry has its own set of characteristics from the types of clients it serves to the types of products it produces. These characteristics cannot help but influence the technologies used and the ways that new technologies are developed and incorporated into the construction process. The sector that will be emphasized in this thesis is the heavy construction sector.
The heavy construction sector, engaged in construction of roads, bridges, dams, etc., is not commonly viewed as a very technologically innovative industry. Yet a wide range of technologies is required for this sector to carry out its function. Heavy construction is an industry that is repeatedly called upon to break previous records (longer bridge spans, faster construction) and to solve challenging problems in unique projects (harsh environments, etc.) Technology (in both engineering and management) is a crucial tool for addressing these challenges, which inevitably push technology beyond the state of the art. Despite the importance of technology, heavy construction does not engage in firm-sponsored R&D nor do many companies actively pursue new technologies for purchase or hire persons with advanced degrees in technological and scientific specialties. Nevertheless, construction firms do manage to procure innovative technologies when they are required for projects.

Thesis

The central argument of this thesis is that the behavior of the construction industry in matters related to technology—learning about, acquiring and developing technology—is a consequence of the strong role of contextual knowledge in the industry. Dependence on knowledge which remains closely
linked to the context in which it is gained results in patterns of behavior which will differ from industries and activities which draw from formal or context-independent knowledge.

The purpose of the research related in this document is two-fold. One purpose is to investigate and explain the diffusion and development of technology within construction. To achieve this purpose a pilot case study was performed which, along with other previous research, indicated a strong reliance on context — specifically on the project as context — in the construction industry. The conceptual framework, presented in Chapter VII, seeks to explain what causes contextual knowledge to be an important factor and what kinds of behavior can be expected from reliance on this factor. A second purpose is to explore and understand how contextual knowledge operates in a particular sector of the construction industry. This purpose is achieved through three case studies of heavy construction projects (including the pilot study mentioned above). The case studies themselves are described in Chapters V and VI. In Chapter VII their results are examined in light of the conceptual framework of contextual knowledge in construction and are used to refine the concepts employed in the model and more clearly define the applicability of the model.
Chapter II

FORMAL KNOWLEDGE AND CONTEXTUAL KNOWLEDGE

Formal vs contextual knowledge

Usually as a field or discipline develops, knowledge becomes more formalized or systematized. This happens as fundamental elements and relationships are abstracted from a multitude of specific and diverse instances. This occurs through a process of analysis: reducing complex processes into component parts, determining the importance of each and establishing their interrelationships, if possible, their causal relationships. The resulting "formal knowledge", although it usually originated in empirical instances, is no longer tied to these particular occurrences but is more abstract and more generalized. Having been formalized, which usually involves the embodiment of the knowledge in words, formulas and/or graphic representations, it is able to be transmitted through formal channels: textbooks, lectures,
papers, etc. These things are the signs of established scientific, intellectual or professional discipline.

But there is also knowledge which is not formalized. It is immediately connected to specific experience and is not completely analyzed, i.e., broken down into elements and relationships that transcend the specific context in which the knowledge was gained. It is knowledge which is not (or not wholly) embodied in words, formulas or pictures and is therefore not easily transmitted through formal means. It remains embodied in the experienced person and is transmitted through direct experience. It is characteristically synthetic knowledge: the knowledge of how the diverse elements of a complex process work together even if it may not involve explicit knowledge of what each of the diverse elements is and specifically how it is related to each of the other elements. Einhorn (1982) puts it this way: “Optimal rules, such as Bayes’ theorem, optimization, etc., are learned deductively. In fact, much of what can be called formal learning is of a deductive character, that is we are taught scientific laws, logical principles, mathematical and statistical rules, etc. Such rules are by their very nature abstract and context independent.” “If heuristics are learned inductively, then learning occurs over many trials with many reinforcements.” And: “If learning occurs inductively via specific cases, then heuristic rules should be extremely context dependent” where “heuristics” here is
closely related to the contextual knowledge discussed in this thesis.

These two kinds of knowledge are not antagonistic but rather complementary. Most human activities involve combinations of both, though different activities may stress one over the other. Theoretical physics may have little need for synthetic practical knowledge and all the formal knowledge in the world does not make one a good parent. Each kind of knowledge has its role to fill. Biology can take a living being apart to learn all its parts in detail but then the living thing loses the quality of being living. Or it can study the living creature as it lives, moves and grows, and forfeit some of the details of its internal workings.

This synthetic knowledge which is so immediately linked to experience of actual circumstances can be called, for this reason, "contextual knowledge." It is knowledge that is and can only be gained in context. The disadvantage of this is that it is so tied to the context(s) in which it is learned that it is difficult to apply in wholly new contexts and, as mentioned above, it is difficult to transmit to people who have not experienced the same contexts. On the positive side, a person with the appropriate contextual experience will be able to apply knowledge in practical circumstances in an effective manner because of his or her personal familiarity with the complex workings of such circumstances,
those complexities and idiosyncrasies that are usually lost in the process of formalizing knowledge.

This positive aspect of contextual knowledge is what makes it very important in the practical application of any discipline whether it be medicine, business or engineering. Structures of formal knowledge tend to be abstract and general. They must often neglect some details, complexity or deviations from the rule for the sake of simplicity or conceptual clarity, but actual performance in any field requires knowledge of how all of these things work together and how they affect the principles and relationships developed in the formal system. In the area of technology this is particularly true because technology is always oriented toward function, not just formal understanding. A technology must work, it cannot simply be a good idea; it is ultimately concerned with practice, not just theory. Any knowledge of practice (engineering, nursing, etc.) always involves a large amount of contextual knowledge, an accumulation in the person of many specific experiences, related by common sense to form a holistic attitude, one that is not fully analyzed and formalized. This holistic knowledge is required for practice because the technologies must not only be understood, but must function – in fact they must function even if they are not understood. For instance, one cannot wait for a complete analytical understanding of soils before building foundations. In fact,
the best geotechnical firms in a region are so because of their experience with the soils of that region. They may not perform well in a new region, even if presented with a very thorough set of boring logs, because they will not have a "feel" for the region. As another example, a baseball player does not necessarily have an analytical understanding of all that is required to hit a home run — his whole organism, body and mind, react as a unit to accomplish this task after months and years of practice. Analytical theories tend only to be able to deal with the few essential elements of a system — something which is very important for formal understanding because of the limitations of the human mind. Contextual knowledge fills in the interstices. This is something like the difference between the jerky, though precise, movements of a robot and the smooth movements of a human being equipped to learn from his or her years of practice in moving.

Conceptual background

Interest in these two kinds of knowledge, or ways that human beings learn and interact with the world, is reflected in various areas of thought and research. What is needed is to recognize and bring into balance two aspects of human learning or cognition. These are sometimes referred to as the "objective" and "subjective" aspects. I have also referred to them elsewhere as acquisition of formalized
versus non-formalized knowledge (Brach 1989a.) Formalization implies fairly certain understanding based on rational explanation. Formalized knowledge is that subset of experiential knowledge that has been systematized and (usually) causally explained. Non-formalized, experiential knowledge, on the other hand, does not require explicit causal understanding of events. It is able to take into account elements of phenomena which have not been understood with much objective or "scientific" certainty. Nevertheless, it is a crucial as the heuristics of the expert when it comes to the successful accomplishment of real world tasks. The key point to keep in mind is that this type of knowledge, by its nature, is intimately bound up with the unique experience of the individual person. Whereas this aspect of knowledge and its relationship to the person has been treated primarily in the field of philosophy, psychology and education, it's practical repercussions are also felt in management and technology.

An example involving both management and technology is that of ill-defined systems. This field is concerned with controlling or managing systems that are not well understood formally. These may be highly complex systems in which the relationships between components have not been charted yet; or systems in which time lags in communication require action to be taken without full information, etc. "To say something is ill-defined is more to describe us than it." (Selfridge
Something is ill-defined because we have not developed a formalized framework of analysis for it. An interesting observation about such ill-defined systems is that human beings deal with them constantly and more or less effectively even without formal definition of the system. One author even suggests that almost any system a human being interacts with automatically becomes ill-defined (Moray 1981.) The same author indicates that it is the acquisition of skills through practice that enables human beings to control ill-defined systems whereas conscious decision making is less well-suited to the task. These observations fit in well with the comments made above concerning nonformalized knowledge and subjectivity. Any system a human being interacts with will leave a subjective impression on him (i.e., produce experiential knowledge.) From regular experience of the system and acquisition of this knowledge responses are elicited and patterns of effective responses to the system are repeated until they form habits or skills. "For humans, action generates skill." (Moray 1981)

Human beings seem to develop internal models of systems that allow them to deal with them effectively (Moray 1981.) These models would be developed subconsciously. But it may be helpful in approaching ill-defined systems to try to consciously develop conceptual models of parts of these systems. Young (1981) takes the point of view of the user of the system in developing such models. He suggests the use of
task/action mapping models in which core aspects of the system's behavior are described in terms of the actions required by the user.

Another area of technology is expert systems. In developing such systems the knowledge and decision-making processes of experts are transferred to the computer. Such knowledge includes not only formal, scientific knowledge such as that found in the textbooks of the field but also the heuristics or "rules of thumb" that each expert develops through years of experience of dealing with problems in his domain. This shows a duality of learning mechanisms: one in which information is able to be taught formally to any number of people independent of their experience and another which is gained only by the individual through actual contact with the domain. To emphasize the validity of such a distinction, it is found that experts themselves are often incapable of pinpointing and communicating these heuristics for "knowledge engineers" to use in expert systems: it seems that at least some of it can only be learned through personal experience; it cannot even be learned from one possessing that experience. These two mechanisms correspond to the objective and subjective aspects of knowledge, the former being that which is externally demonstrable and thus able to be communicated, verified scientifically and agreed upon and the latter being that aspect that is uniquely possessed by the knowing subject.
Technology development and contextual knowledge: related research

Much work has been done toward the development of a formal body of knowledge concerning technological development. Several major studies have sought to relate technological innovation to scientific activity (TRACES and Hindsight, for instance.) Schmookler (1966) began to establish the link between technological progress and economics. The role of users and the immediate sources of innovations (von Hippel, 1988) and the critical organizational roles and characteristics necessary for innovation (Roberts and Fusfeld 1983; Allen) have been documented. At the level of these particular issues the field is becoming fairly well understood. Nevertheless, the overall system of technological development is not well-defined. No one model of innovation or development answers the majority of questions adequately. One reason for this would seem to be that much of technological innovation is still crucially dependent on personal roles and skills: the critical roles discussed by Roberts (1983), the gatekeeper well-documented by Allen (1977), the importance of user for certain types of technologies (von Hipple, 1988; Gamser 1988.)
One particular branch of research which seems to strongly suggest the importance of contextual knowledge is that concerning sources and patterns of communication in science and technology. Much work in this area has been done by Prof. Allen who describes a fundamental difference between science and technology and its effect on communications and knowledge. He says that science is universal whereas technology is not; technological problems are defined differently for different countries and even different companies (Allen, Tushman and Lee, 1979.) In terms of formalization this could be restated: science is a formal body of knowledge with a formal language that can be communicated in literature and lectures whereas technology is more related to specific experiences and not easily communicated to other technologists of different experience through formal written or spoken channels.

Allen points out that the formal flow of information in science is facilitated by the compatibility of input and output in science. Both input and output are verbally ("formally") encoded so that the output of any scientific endeavor is already in a form easily communicated to other scientific endeavors. Technology, on the other hand, receives verbally encoded input but its direct and predominant output is information physically encoded in a product or process (a technology) and is thus not well-suited to be input for further technological endeavors. Any
verbally encoded output from technology is a by-product which does not adequately communicate the technology itself. Thus the flow of knowledge in technology is not continuous. (See Figure 1.)

Thus he finds that scientists communicate more effectively through scientific literature than engineers do through technological literature. "[P]ublished information is at best secondary to the actual utilization of the technical innovation" (Allen, 1977 p. 40.) Technology's legacy "is encoded in physical, not verbal, structure." The ability to encode something adequately in a verbal structure is a sign of its formalization. All scientists trained in the same area, knowing the same theories and concepts and the vocabulary used to express them can understand most of what is presented in the literature (at least in theoretical parts of science.) Technologies, on the other hand are understood best by experience with them. The phenomenon of "gatekeepers" has sprung up to meet this problem. A gatekeeper is an individual in an engineering firm who reads the technical literature and deals with outside colleagues more that the other engineers do. It appears that he does so effectively because he knows how to "translate" this outside information into a form that his colleagues in the same firm can utilize. He can do this because he knows their work and has high technical competence and a lot of experience himself. An interesting question related to this research is
Figure 1

Verbally encoded information (papers and discussion) → SCIENCE → Verbally encoded information (papers)

Verbally encoded information (papers and discussion) → TECHNOLOGY → Physically encoded information (hardware and other products)

Verbally encoded information as by-product (documentation)

Source: Allen (1977)
whether something like a gatekeeper exists in the construction industry.

Tushman and Katz (1980) discuss the need for a formalized concept of a task for the development of a common language for communication at levels more abstract than direct personal experience. They look at the relationship between the type of task and the existence of a gatekeeper in research projects. The types of tasks were placed on a scale from more universal to more local: basic research, applied research, development and technical service. In a nutshell, the gatekeeper was found to be more important in locally defined tasks than in universally defined tasks. Allen and De Meyer (1982) in a study of Swedish firms also find a link between the type of task (technology) and the importance of literature or gatekeeper communication. In another paper De Meyer (1982) proposes two characteristics of a technology that affect its international transferability: 1) its analyzability -- the extent to which the technology is characterized by a high level of analytical tools versus craftsmanship, and 2) the level of experience of the company with that kind of technology. Thus it seems there is some precedence for looking at the relationship between the nature of technology and its movement (acquisition or development) based on the need for communication at the personal, experiential level.
The importance of the individual experienced person to technological development is even more general than the restricted circumstances of special "roles" like that of a gatekeeper. The nature of technology in general as oriented toward performance, not pure knowledge, leads to this: only a portion of knowledge regarding a technology can be formalized, the rest is embodied in the persons involved through their experiences.

If one takes into account not only the formal knowledge that is part of technology but the knowledge that is embodied in the experienced persons, Allen's diagram of information flow in technology can be revised and continuity can be found in the development of technology. Besides the information that is physically encoded in the products of technological development, there is also the information or knowledge that is encoded in the experienced persons who develop and use the technologies. This knowledge is easily overlooked because it is not formally (verbally) encoded nor is it "in" the technologies themselves. It is this synthetic, holistic or contextual knowledge discussed above which is possessed by the experienced person. This in turn becomes part of the input to further technological developments. What is then crucial for continuity in the development of technology is the presence and involvement of the persons in whom the required types of experiential or contextual knowledge resides. As much of this knowledge as can be formalized can
certainly become part of the verbally encoded output and input but what cannot be or is not formalized requires the appropriate person. (See Figure 2.) "[A]n art which cannot be specified in detail cannot be transmitted by prescription, since no prescription for it exists. It can be passed on only by example from master to apprentice." (Polanyi, quoted in von Hippel 1990.) "The transfer of craft knowledge ... is a matter of acquiring skill. An apprenticeship, or at least a period of interpersonal interaction, is thought to be the necessary prelude to the transfer of skill-related knowledge." (Collins 1987)

Technological development in the construction industry

While all industries would need to rely on contextual knowledge to successfully implement their technologies, construction seems to be particularly dependent on this kind of knowledge. The history of industries sheds some light on the importance of these different kinds of knowledge and the resulting approaches to problem-solving and development of technology. Construction is a very old industry that grew up in response to fundamental human needs of shelter, water, transportation, defense, etc. It has developed largely through experience or practice because such needs often cannot wait for "scientific" solutions. On the other hand, industries such as electronics, chemicals, advanced
Figure 2

- Verbally encoded information
- Contextual knowledge

Technology

- Physically encoded information (hardware/products)
- Contextual knowledge embodied in the person
- Verbally encoded information as a by-product (documentation)
materials, nuclear energy and biotechnology can trace their origins to specific scientific or technological discoveries if not to the development of a scientific field itself. This is not to say that all technologies in these fields are completely understood scientifically nor that every technological development is the direct result of a scientific discovery. But there is a link between the formal methods of inquiry used in modern science and the development of technologies in these industries. It is also important to point out that the above statements will be true about a sector of the construction industry to the extent that that sector conforms to this industry description. Heavy construction with its often unique and complex projects is more likely to depend more on contextual knowledge than housing with its somewhat more uniform and simple product, much of which now can be constructed in the more controlled environment of a manufacturing plant rather than the diverse and unpredictable environment of most heavy construction projects.

Clearly this distinction between a more formal approach to problem-solving and a more informal one is not perfectly correlated with a distinction between industries. All technologies do develop through practice by virtue of the fact that they are functional things which are actually used. But the difference between construction and more R&D-intensive industries is more than one of degree. Rather it
seems to lead to a wholly different approach to technological development.

The key to technological development in construction, and therefore to the argument developed in this thesis, is construction's greater reliance on contextual knowledge than other industries that form the standard for technological development.

In those industries more closely tied to scientific and technological developments firms often engage in a large amount of in-house R&D or invest in R&D in universities and other labs. The R&D approach of these industries could be described generally as an active, and in some cases aggressive, pursuit of new knowledge for the purpose of developing or acquiring specific kinds of products and processes. It often involves an active marketing component to ascertain what will sell and how to sell it. The reputation of such firms is often highly dependent on the possession of and sometimes the actual development of new technologies. These characteristics are reflected in the measures used to judge the capacity for technological development in these industries, measures like R&D as a percent of sales and the proportion of PhD's hired. Numbers of research publications, patents and square feet (or acreage) of research facilities become prominent characteristics for attracting investors and clientele.
When these kinds of characteristics, valid for the industries in which they arose, are assumed to be the sole or the best indicators of an innovative industry, construction inevitably appears non-innovative. As was noted earlier, very little research is done that is directed explicitly toward the construction process. Innovations are often developed in what are considered separate industries: suppliers of materials, components and equipment. Individual construction firms rarely if ever perform or fund R&D themselves. They hire few PhD's, publish few papers and may consider even the talk of "research facilities" to do more harm to their reputation than good as many construction companies believe, with good reason, that their clients do not want to see them engaged in anything that could be construed as an increase in overhead expenses.

There appear to be good reasons for this state of affairs in construction. Codes and regulations are often cited as obstacles to innovation because of the inflexible demands they make. Interfaces between disciplines or between trades onsite can be difficult to negotiate when new technologies are introduced. Risk of failure and the corresponding liabilities can be formidable to most contractors. And above all, there is a lack of economic incentive to engage in innovation: for most types of technologies contractors (and designers) have little or no
incentive to invest in innovation because they will not be likely to reap the economic benefits. This is due to the difficulty in patenting and protecting patents of construction technologies or maintaining them as trade secrets. They are often easy to see in order to imitate and easy to modify to avoid patent infringement. In other cases the individual firm may not be able to assure itself a large enough volume of work requiring a particular technology to make the technology pay off. In addition, it is so easy for contractors in some sectors of construction to acquire the technologies they need just for the project at hand that there is little advantage to possessing technologies for special types of projects.

Nevertheless, as mentioned earlier, construction does use and develop new technologies. This thesis intends to demonstrate how and why the acquisition and development of technology in construction takes place in a project-centered manner, a manner in which the knowledge gained in context can be taken full advantage of.

The project-oriented nature of construction business is indicated by Tatum (1987). He states that "project demands force many innovations." This project-oriented behavior fits in with the ideas discussed in the text about the need for contextual knowledge in less formalized fields. Construction itself is not a very well formalized field. It is next to
impossible to teach; those who know it know it by experience. The lack of general, formalized knowledge about the construction process makes it difficult to communicate technological needs for whole sectors of projects and to develop general solutions for these needs. Thus it is natural that technical development should focus on the needs of a particular project. Most construction companies compete not on the basis of technologies but on the basis of expertise, experience-derived skill in particular types of projects. Even at that, each project is considered unique and technologies are gathered together just for that project. Where a market-oriented, rather than a project-oriented, approach is taken, the technologies are not so much related to construction as to processes that go on within the constructed facility: chemical and nuclear processes, for instance. These processes stem from much more formalized knowledge concerning basic science and process design. Thus this knowledge is more generally applicable — the processes will be performed in largely the same way inside any process plant. Although such process technology, as all technology, requires experience to be used well, it is easier to teach at least the formalized aspects of it.

Construction is an interesting industry in which to study this interplay of formal and experiential knowledge precisely because of its project-oriented nature. In a production line of a factory, each piece is exactly the same
as the others in the line — or it should be. The environment in which production takes place is controlled (and often constant) so essentially the same "knowledge" is needed to produce the first unit as to produce each one after that. Nearly 100% of the knowledge is generalizable and therefore formalizable. In heavy construction, on the other hand, each unit is unique. A smaller percentage of the knowledge needed to build a unit is generalizable (formalizable.) The remainder of the knowledge is contextual — each project is a largely new experience. Experienced personnel know how to learn quickly in each environment to make up for the relative absence of formal knowledge. Construction then becomes an excellent laboratory for studying the role of contextual knowledge. Nevertheless, results of this research should contain elements that are generalizable to other industries since all industries contain both kinds of knowledge.
Chapter III

METHODOLOGY

The importance of context and therefore of the project

I have chosen to study construction technologies in the context of the projects in which they are used by a company. There are two reasons for this. First, it reflects the project-orientedness of the construction business in general. Previous research of mine (Brach 1989b), as well as research by Tatum (1987), suggest that decisions about technologies are often made in a project-oriented fashion. This approach will then be more familiar to the interviewees who think of technologies as means to accomplish specific projects. The second reason for looking at technologies within the context of projects is somewhat akin to the reasons for studying animals in their natural habitats. It allows one to see how the technology performs in its "environment" and, particularly, how it interacts with other technologies.
Technologies are instruments, means to other ends, and as such rarely if ever perform in isolation. They work in conjunction with other technologies (and with people) and often require or give rise to other innovative technologies. Often these are small and easily neglected although they may be crucial to the successful performance of the more obviously innovative technology. These ancillary technologies can be discovered by looking at projects rather than isolated technologies.

Description of method followed

**Case study of a construction firm**

The first contribution to this research was a project performed one summer for a construction firm. The purpose of that research was to determine the means used by U.S. construction firms to acquire technologies for innovative projects. That research project pointed strongly to a project-oriented approach to acquiring technologies: rather than a market-oriented approach construction companies set about procuring the technologies they need to successfully implement the project at hand with little or no acquisition of technology intended to enhance the firm's overall position in the market.
A case study approach was used for this research. It consisted of selecting particular cases of construction projects and construction firms and studying how technologies were procured in each case. The case study method is good for studying phenomena which are not well-understood. It would be accurate to describe technology acquisition in the U.S. construction industry as one such phenomenon. The case study method allows a broad and flexible approach which can help the researcher begin to understand a complex occurrence. On the other hand, because one is dealing with only one or a few specific cases, the results may not represent the general or typical situation. This should be kept in mind when reading the descriptions and results of the case studies.

Five cases were chosen for study. Two different focuses were used for these case studies:

Project focus: Three case studies concentrated on particular construction projects. Projects were chosen for being innovative in some way and therefore requiring some new or less common technology. Such technologies were identified for each project. Then the method that the designer or builder used to acquire the technology was ascertained.

Firm focus: Two case studies concentrated on a particular firm and its range of technology procurement methods. Unlike the project focus, this approach allows one
to look at the overall pattern of technology procurement behavior exhibited by a firm. Variation in methods of procurement with types of technologies can be studied and the firm’s strategic planning in the area of technology can be more evident. This strategy can include the acquisition of technologies over the long term to be used on more than one project, something that is not easily seen in a project level analysis.

In this thesis only one of the firm case studies will be discussed as it represents my personal contribution to the overall project. That case study involved telephone interviews with the following individuals at the construction company being studied:

The president and chief executive officer who outlined the various types of projects the firm engages in and the various ways they keep abreast of technology.

The manager of marketing services who provided more detailed information about the company’s activities.

A manager of "advanced" projects.

The project manager of a bridge rehabilitation project.
The types of questions asked of the first two individuals interviewed were:

What kind of technological benefits arise from your company’s university contacts?


Has your company ever acquired a company for the sake of specific technologies possessed by that company? Examples.

Does your company engage in joint ventures for the sake of access to new technologies?

Please give examples of incremental improvements developed on a project-by-project basis.

Has your company ever invested in the development of a technology that would be of benefit outside of only one specific project?

The latter two individuals mentioned were interviewed with respect to details of how they acquired new technologies on particular projects in which each was involved.

Pilot study.

From here came the impetus to study patterns of acquisition of knowledge about construction technologies. So a pilot study was conducted in the form of a case study of
the Post Office Square (POS) parking garage in downtown Boston, MA. The pilot study was designed to more clearly identify the elements that may be involved in what appeared to be the transfer of "informal" knowledge about construction technologies through "informal" means of communication.

The study of the POS project involved three activities: interviews with key participants in the project; review of newsletters, newspaper articles and professional papers arising from the project; and a site visit.

The following individuals were interviewed:

Steve Barlow - project manager, J.F. White, general contractor
Richard Blouin - project engineer, J.F. White
James Becker - president of Beacon Construction and head of construction committee for the owner, Friends of Post Office Square (FPOS). Beacon Companies is part of FPOS.
Roy Stifler - construction consultant to FPOS
Eldon Abbott - project manager with Parsons Brinckerhoff, the lead designer on the job
David Schoenwolf - senior engineer with Haley and Aldrich, FPOS's geotechnical engineer
Mark Haley - vice president at Haley and Aldrich, also involved with the POS project
Professor Robert Whitman - Professor of Civil Engineering at MIT, member of the Technical Advisory Committee for FPOS and chairman of the Geotechnical Monitoring Committee for FPOS

The interviews were all conducted face-to-face. Certain basic questions were asked of each interviewee but the interviews were generally open and the respondents were encouraged to comment on any aspect of the technology or communication in the project that they thought relevant. The basic questions were: What was your (your company’s) role in the POS project; what specific “talents” or expertise did you bring to the project? What were the new or unusual technologies used in the project? How and from where/whom was knowledge of these technologies gained? Had you heard about or used these technologies before yourself? In general, how do you go about learning of new technologies; what kind of investment do you make in this activity? I also asked respondents about their own educational and professional experience.

Several newspapers and trade magazines (see references) carried articles on the POS project, describing the top/down construction method and emphasizing the private-public cooperation that has pushed the project ahead. FPOS published a construction newsletter, Constructionews, to introduce neighbors to the participants of the project and
inform them of progress. Two professional papers were written for publication by participants in the project. "Field Instrumentation Program Plays a Vital Role in Deep Excavation Project" (Whitman, Johnson, Abbott, Becker) describes the "extensive field instrumentation, monitoring and evaluation program that was implemented" for the POS project. This program was unusually extensive and "the information collected was relied upon heavily during critical stages of the 'top-down' construction method to provide a reliable basis for development of appropriate sequencing and scheduling strategies." "Up/Down Construction - Decision Making and Performance" (Becker, Haley) discusses the decision processes involved in and the performance of three projects in Boston using top/down construction: Rowes Wharf, 75 State Street and the Post Office Square Garage. Other related papers written by POS participants were also helpful: "Rowes Wharf: A Case Study in Substructure Innovation" (Becker) and "Foundation Considerations for the Expansion and Renovation of the Hynes Auditorium" (Johnson and Schoenwolf).

Well into the project I visited the construction site and was given a tour by Mr. Barlow. At that time the seventh and final level was being excavated so I was able to watch this operation, as well as view some of the newer products in use and the methods developed on that project.
Other interviews contributed to the interpretation of the POS case study. These interviews involved two groups of people. The first are executives from large U.S. construction companies:

Thomas W. Harrison - Manager of Projects, Construction/Maintenance Support, Fluor Daniel, Greenville, SC
Donna Cusson - Manager of Research and Development, Perini Corporation, Framingham, MA
Frank H. Thomas - Vice President, Research and Technical Services, Turner Construction Company, Chicago, IL

These interviews were conducted over the phone. They served to provide some comparison with other firms doing a variety of projects in different parts of the country. Questions asked included: How does your company acquire technologies for construction? Does the acquisition of technology differ with the type of project? Who investigates new technologies and makes the decisions regarding acquisition? What role do you see technology play in your competitiveness? Does your company ever license a construction technology or develop a technology in-house?

The second set of interviews was conducted face-to-face with two individuals who study the construction industry or some part of it:
Edith Page - Project Director, U.S. Congress Office of Technology Assessment, Program in Science, Education and Transportation, Washington, D.C.

Andrew Lemer, Ph.D. - Director, Building Research Institute, National Research Council, Washington, D.C.

These individuals were able to give some more general perspectives on the technological situation of the U.S. construction industry (and some comparison with other industries) as well as recommendations for research.

Second and third case studies.

From this "pilot study" a conceptual framework was developed of the role of contextual knowledge in education about and in the acquisition and development of technology in construction. To further clarify the elements and relationships in this conceptual framework two more projects were chosen as case studies. The first was part of the North Station Transportation Improvements Project (NSTIP) in Boston, MA and the second was the Jamestown Verrazano Bridge in Rhode Island.

As with the Post Office Square case study, data were collected through interviews with various personnel on each project. Many of these interviews were conducted face-to-
face but several were telephone interviews. Face-to-face interviews were especially helpful at the beginning of each case study when the overall picture of each project was being explained and the basic technologies described because the interviewee could use visual aids in these explanations. Telephone interviews seemed to suffice when straightforward information was needed without much description of technical details. Interviews conducted over the phone are noted as such below.

The individuals interviewed for the North Station project (referred to as NS) were:

Joseph Clougherty - senior project manager of NSTIP, from the Massachusetts Bay Transportation Authority (MBTA), owner
John I. Williams - project manager, Design/Development; Construction Directorate, MBTA
Rory Neubauer - senior project manager on NS, Modern Continental, general contractor, in joint venture with Ohashi Construction
David Coleman - The Millgard Corporation, specialty subcontractor for construction of interior caissons on NS
William Osler - Advanced Track Products, manufacturers of acoustical track fasteners to be used at NS (phone)
David Towers - Harris Miller Miller and Hanson, acoustical consultants to the designers (phone)
Mark Pelletier - project engineer, Parsons Brinckerhoff/Seelye Stevenson (PBSS), Joint Venture, designers (phone)
Richard O'Brien - project manager, PBSS (phone)
Nino Catalano - vice president, ICOS Corporation of America, specialty subcontractor for perimeter slurry wall and Green Line tunnel portion (phone)

The individuals interviewed for the Jamestown Verrazano Bridge project (referred to as JVB) were:

Warren Pettingell - project manager, Perini Corporation, construction manager; senior vice president of Perini
Richard Walsh - project manager, Atkinson-Kiewit Joint Venture, general contractor
Michael Veegh - VSL Corporation, post-tensioning subcontractor and lifting contractor (phone)

Both case studies also involved site visits and reading of newsletters, articles and technical papers related to the projects themselves or the technologies used.
Chapter IV

CASE STUDY OF CONSTRUCTION FIRM

The summer research project described in Chapter III involved five case studies: three centered on specific projects and two on firms. This chapter presents the detailed results of one of the firm case studies and summarizes the results of the entire research project.

Results of interview

This section relates the answers given by the manager of marketing services of the firm being studied. The responses were given over the phone and in writing.

1. The company belongs to various organizations through which it can obtain information about the state of the art in technologies. For instance, they belong to an organization concerned with rapid underground construction,
the American Concrete Institute, the International Commission on Large Dams, etc. The company's employees read these organizations' periodicals, attend conferences and give papers about their experiences with various technologies. Membership in such organizations provides an avenue for informal sharing of know-how as well as keeping up with what others in the same field are doing. It undoubtedly also makes the company's name known among people who may require a contractor with experience in these technologies.

2. The company does not fund any research directly, it does belong to a university's construction research program. In this relationship the company often helps students by providing them with information for their research. They also receive reports of research being performed at the university from which the company occasionally learns something beneficial to its business.

3. Incremental innovations (small improvements, usually in construction procedures) occur with some regularity on construction jobs. The company does not seem to have any systematic method for taking notice of and spreading such improvements but they do spread through several means: job-site visits by engineers, managers and supervisors; periodic in-house meetings through presentations and conversations; and frequent exchange of personnel from one subsidiary company to another.
4. The company engages in joint ventures in order to compete for highly desirable projects. Sometimes a joint venture is entered into because one firm has a specific technology, but this does not seem to be common. See point number 7.

5. Acquisition of firms is another strategy of the company. Examples were given of four firms that were acquired. These firms were all acquired in order to gain access to a geographic market. They also provide expertise in the design or construction of certain types of facilities. They did not appear to provide any specific technologies (products or processes) but rather the know-how that comes from experience and the recognition and professional contacts needed to win jobs in a particular location.

6. When the company encounters a problem in the course of a project that neither they nor their subcontractors have experience to solve, they will contract another firm or consultant to solve the problem. For example, for one project the company hired an engineering firm to design a shoring system to support a platform for a two 100-ton cranes. This course of action seems to be quite characteristic of the company as will be seen in the more detailed examples described below.
7. Occasionally, the company may need a technology which is patented or proprietary for use on a specific project. In this case, the company will negotiate an agreement in the form of a subcontract or joint venture with the company that holds the rights to the technology. They do not acquire access (by license or contract) to a technology for use on future, unspecified, projects, but only on a project-by-project basis.

8. On several projects the company has pioneered the use of a particular technology, previously developed elsewhere. For instance, on one project they used probing devices to indicate the presence of methane or abandoned utilities for the first time. They also used jet grouting for the first time in a tunnel in the U.S. In the same project, a different approach was taken for grouting. Instead of injecting grout from the surface, it was injected upward from within the tunnel. This approach saved about $100,000. In instances like these the company relied on the knowledge and experience of specialty subcontractors to implement the technologies. Again, this will also be shown in the detailed examples.

9. There have been instances on the company's jobs where new technologies, whether products or procedures, needed to be developed. These technologies included methods for generating electricity, welding methods, management
techniques, a new tunnel boring machine. The company's role in the development of these technologies is basically one of managing the R&D resources. The company usually contracts out all research and development work on a project basis. The expenses are project expenses. Usually, the expense of R&D is totally assumed by the owner although there have been instances where the company had to absorb some of the cost. The next section contains more detailed descriptions of technological developments on the company's projects. These will make clearer the way in which the company operates with respect to technology.

Technological development on a project basis

This section relates instances of development or acquisition of technologies on three particular projects.

A power plant

It was decided by the owner on this project that the tunnel boring machine (TBM) should be used rather than conventional drill-and-blast techniques because it was more economical and created a hydraulically superior tunnel. The owner also determined that a new TBM should be designed rather than using existing machines. A manufacturer was commissioned to design and build the new machine.
The contractor of this job was a joint venture consisting of three companies, one of which is a subsidiary of the company being studied. This subsidiary has heavy construction expertise. It was through this subsidiary that the company exercised some influence over the development of the new TBM by requesting special features that could enhance reliability and improve tunnel production. Examples of such requests include secondary lubrication and water spray systems to allow operation to continue while preliminary systems are down for maintenance or repair.

An energy conversion project

This particular project involved the first use of an innovative means of generating electricity. The project and subsequent similar ones were undertaken by the company being studied, another non-construction company and one of the States.

The company's manager of advanced projects explained that the company's role in this and similar innovative or "high-tech" projects is one of manager. The company has no laboratories and hires no researchers. Rather they hire, by subcontract, the scientists, designers and testing labs required to develop the technologies needed for the projects. This manager says that the company is very interested in and keeps up with new technologies that could be related to
future projects. This is particularly true in the particular State in question in the area of alternative energy sources. But the company does not perform its own research in these areas or invest in others' research. The company coordinates the work of university scientists, consultants, government agencies and builders to produce an innovative project.

In the case of these energy-related projects, most were funded by the Department of Energy. An exception was the very first such project which was funded by the State. In this project, the company being studied and the other non-construction firm agreed to work at cost to demonstrate the new technology. There was a misunderstanding and this was interpreted to mean that these companies would not charge any overhead so these two companies lost money on this job and consider it their "donation" to the project.

Naturally, such projects involve a certain amount of risk. It is difficult to know beforehand how much R&D must be done to solve the scientific and technical problems and to produce a working product or process. The company is protected from this financial risk by working on a cost-plus-fixed-fee basis so uncertain R&D costs do not become their burden but the burden of the Department of Energy. Another type of risk is that of subsequent failure of the technologies followed by possible lawsuits. The company
protects itself in this area by taking out insurance and by emphasizing safety programs on their projects.

**A bridge rehabilitation project**

The project manager on this project described some of the technological features of the job. One aspect for which this project was highly acclaimed was the welding technique employed. An 80% penetration weld was specified because it is cheaper and easier to do. Some particular aspects of an 80% penetration weld configuration for orthotropic bridge decks were developed by a State research organization for a bridge that was never built. The company set about to make sure that such a weld would in fact work. For about three or four months, the company experimented with running the welds. They hired a welding engineer who took a welding foreman and purchased the equipment that was on the market and experimented with the welding technique. There was no special item in the budget for such testing; it was just something that had to be done before work began on the bridge. Both semi-automatic and automatic welding were used on the deck, both of which were newer techniques, still under development at the time. But this is knowledge that can be "hired" through subcontract.

An important aspect of the job from the company's point of view was the scheduling and the coordination of resources.
A unique characteristic of the job was that they had to work at night and release traffic lanes, complete, for use in the morning. To accomplish this there were many options; it was the company's job to see what they were and to coordinate the best set of methods for completing the project. For instance, the company's main accomplishments of note on the project were:

- To study transportation options. There were many possible ways of getting materials to the site so the company had to study each one and the necessary operations accompanying each transportation mode. Originally, it had been thought that deck parts would be transported by water but the company found it was not economical. A tug boat would have to wait around for long periods of time, but a truck could just bring the deck segments in, take them to where they belong and leave.

- To determine how segments would be handled on the bridge. They considered tower cranes, gantry cranes, etc. They ended up using crawler cranes at the yard where the segments were being produced and a rough terrain crane at the bridge. This is a somewhat unusual use of the rough terrain crane but it was found to be the best for the job. Gantry cranes are not flexible enough. They did need to modify equipment slightly, for
instance making sure outriggers were big enough to
distribute load on a seven inch concrete deck.

- To determine other aspects of handling the bridge
deck segments. For instance, they found that the
segments needed to be placed at a 45° angle at certain
points in the process. Some segments had to be
transported in two pieces and welded just before going
onto the bridge. They were not permitted to weld lugs
onto the deck segments for picking them up so they had
to figure out another way to handle them. They
developed a small piece that could be attached to the
edge of the segment by which it could be lifted from the
truck. The rigging for every job is unique so specific
rigging configurations also had to be devised.

In order to assure that all the necessary materials,
etc., were at the job site each night, the company tailored
existing management software. They used a package that
included a database and a scheduling program. The database
was used to keep track of all the different materials for
each section of the deck. They would then get a complete
printout of this information so they could be sure that
everything needed for each night's work would be available.
This was crucial since each night a section of work had to be
begun and completed by morning - they could not afford to
forget some part. They also modified the database to make a
bolt inventory. This all really represents using the inherent capabilities of today's computer technology, rather than development from scratch. Though this package contains a scheduling portion the company did not link up the inventory with the scheduling.

Analysis of all five case studies

Once all five case studies were completed, their results were brought together and analyzed. The single most striking aspect of the three project cases was that in every case the technology, regardless of its type, was purchased for the project. In some cases it is a question of buying a product, in others it involved hiring a consultant or designer. In the case of design-related technologies the owner or designer purchased the technology. In the case of construction technologies the contractor purchased them. But in no case did owner, designer or contractor invest in any research and development. Neither had any party previously acquired rights to a technology or acquired a firm possessing the technology. All were available on the market or as fairly general industry knowledge. In the one case where a proprietary design technology was used it was the owner who was to pay for the rights to use it, not the designer who subcontracted the design to the inventor or the builder who built the design. And for that matter, at the time the case
study was written, no royalties had yet been paid even though that portion of the structure was complete.

Essentially, the technologies were "hired" by the designer or builder with no more investment or risk than if he were purchasing standard equipment or materials. The cost of learning by trial and error how to erect the technology could represent a certain investment that will pay off in future jobs where this experience would be useful. In two cases the builder developed better ways to erect certain parts of the facility through experience on that particular project. This undoubtedly cost him money because he had to go through a trial and error process. This cost is an investment that should prove useful in winning future jobs and completing them more efficiently.

In these case studies the source of the technology was ascertained and, wherever possible, traced one step beyond the contractor or designer on the current project. Those technologies that were acquired from the contractor or designer were obtained by them (the contractor or designer) through experience or general industry knowledge. This may be the main source for design and construction process technologies since their livelihood stems from the ability to design and build these facilities. They are paid for their ability to do this well, an ability which comes from practice. On the other hand, those technologies obtained for
the project through suppliers (including manufacturer/suppliers and consultants) are often developed by the supplier. All of these technologies are products. These suppliers make their money selling products, not expertise in running a project, so they had more incentive to develop products so they can sell them.

Another striking thing about these findings is that there was no difference in method of technology acquisition between the public projects and the private project studied. Initially, it was expected that the different economic incentives (profit motive and intention of doing similar jobs in the future) and the greater freedom in accepting and rejecting bids might mean that the parties involved in the private project might have incentive to invest in R&D, whether in-house or contracted out, to solve problems of general use to them or to develop proprietary technologies for use on various projects. In fact, though, all the required technologies were purchased or hired through consultants in the commercial building project.

This is not to say that technological development did not take place on this project. As in the public projects, some incremental increases in know-how were acquired. In addition, wind tunnel and shrinkage analysis techniques required for the design were improved by having to deal with the unique problems of this project. In fact, the use of
such analytical techniques is one way in which the private project differs from the public project. In particular the need for a special analysis of concrete shrinkage is an indication that some new problems were being faced in this project. The solution of these problems represents progress in concrete design and construction. Such progress will be useful for future projects of the owner, designer and builder.

The firm case studies were aimed at discerning the overall approach of a company to technology acquisition. Construction products appeared to be purchased from a manufacturer or supplier. Sometimes, as in the case of a tunnel boring machine, no existing product serves the purpose so the manufacturer develops a new one. The contractor may provide some input to the design, but actual design and production of the product and development costs are handled by the manufacturer. Depending on whether or not the product will have any larger market beyond this project, some or even all of the cost of development may be passed on to the owner through the contractor.

Sometimes more is needed that a specific product. A project may require project- or facility-specific expertise. This means experience in all aspects of completing a particular type of product. Such experience usually resides not in a product, process or even a single person, but in a
group of people. In these cases an appropriate firm can be subcontracted or a separate contract can be established with the owner.

At other times the expertise required is more discipline-specific: materials development, thermodynamics, etc. In these cases an individual consultant or consulting firm will be hired. These are often individuals with high academic qualifications or formal specialized knowledge. Their specific knowledge usually only applies to one small area of the project.

Another kind of more specific knowledge refers to construction processes or procedures like the jet-grouting used on one project. These may be known by people with certain formal knowledge but their more valuable asset is their experience applying that knowledge to various construction problems. These people usually belong to firms with a reputation of work in that area. These firms are hired by subcontract for various projects.

Often on a project the craftsmen and supervisors will discover ways of improving construction methods and tools. These improvements are usually small and require very little investment since they often use whatever materials are at hand on a project. These "developments" take place on-site and are usually spontaneous, unplanned occurrences. In some
firms a formal system exists to promote such innovation and to spread the ideas to other projects if they are found to increase productivity.

The primary role of general contractors is to manage the construction of a project. Development of construction management procedures for planning, estimating, scheduling and coordinating are crucial to the success of a project and to the profitability of a construction firm. Developments in these areas often take place within the firm. Such developments may be identifiable products or procedures, but often they are a collection of procedures, knowledge and practice that simply make a project work. Managing a project involves learning how to coordinate various types of technologies to complete various types of projects. It also involves formalizing or systematizing experience gained from a given type of project. This is one way that a firm develops its own expertise in a particular type of construction.

Facility-related processes are the processes that go on inside a facility rather than processes for constructing the facility. They include chemical and petroleum processing technologies, resource recovery and other industrial processes. Sometimes a construction firm can win jobs because it possesses proprietary technologies of this type and can build them into the facilities it constructs. These
are unique technologies compared to the others studied in this research project because they are usually more easily protected by patent or as trade secrets. Construction processes are visible to everyone. Incremental improvements may not seem to be worth patenting. But processes used in a facility can be hidden in that facility. Because they can be held proprietary such technologies can provide a real competitive advantage to a construction firm. For this reason, some construction companies do invest in these technologies, either through obtaining a license to use them on many projects or by funding research in this area, whether in-house research done by a subsidiary or even a parent firm or research contracted to a university or lab.

Conclusions

In summary, three basic approaches to technology acquisition were found in this research:

1. Most know-how type technology (special construction processes, facility-level, disciplinary) is acquired through hiring the know-how in the market place usually through subcontracting. The know-how is embodied in individuals and groups of individuals; one cannot buy or develop a product, one must hire the people.
2. Construction products, whether proprietary technologies or not, are purchased from manufacturers or suppliers of those products. This is because there is usually no incentive for a builder to produce them. The builder's economic gain comes from managing and building. Possessing a proprietary product technology generally does not improve his gain in these endeavors. To gain from the development of a product he would have to sell the product, which is what a manufacturer or supplier does anyway. Sometimes a builder will acquire or begin his own manufacturing capability. This was not studied in this research.

3. Technologies and know-how related to construction management: planning, scheduling, etc., are developed in-house by the construction firm's own personnel. Sometimes this is done systematically with a long-term view (for instance, software development). Other times the development occurs through cumulative project experience since each project may require improvements or new ways of managing labor, materials, etc., that turn out to be helpful for future jobs.

This research has revealed two basic attitudes toward technology procurement in the U.S. construction industry. One is project-oriented and the other is market-oriented. From the data gathered here, the preponderance of technology
acquisition occurs in the context of a project. Technologies are acquired mainly for their usefulness on the project at hand, not usually for any longer term plan. In other words, specific product and process technologies are not usually viewed as instruments for competition in the market place, but as tools for completing individual projects.

There are two exceptions to this trend found in the data. One is the procurement of facility-level know-how through the acquisition of firms possessing that know-how. Even in these cases though, technical know-how may not be the sole or the primary reason for the acquisition. A firm may be acquired because of its reputation and contacts (among designers, subcontractors, politicians) in a particular geographical location. Of course some people may consider these things as part of technical know-how, which can be a very broad concept. The other exception is the procurement of facility-related process technologies through long-term licensing or actual investment in technology development.

If a firm chooses to compete on the basis of expertise in construction facilities that involve sophisticated or specialized technologies, then it will be interested in possessing some knowledge of these technologies, if not the technologies themselves. Technology becomes an important tool for gaining a larger part of the market for those facilities. Possession of the appropriate technologies, if
they are proprietary and expensive to develop, forms an entry barrier to other firms that may wish to compete for those facilities.

On the other hand, a firm may compete on the basis of flexibility and ability to tackle diverse and even new types of jobs. To compete in this way it is not so advantageous to possess certain specific technologies. It is more appropriate to possess knowledge of the technological resources and the ability to coordinate these resources. Thus to increase market share or volume of work a firm may emphasize its diverse and successful experience and develop better ways of coordinating and managing jobs.

So depending on the type of work the company does and the way that it positions itself in the market, it will either view technology as part of a long-term market strategy or as the tool to accomplish specific project. In the latter case, technology does not contribute directly toward long-term competitiveness but only indirectly inasmuch as successful completion of project - due to successful coordination of technology - contributes to the firm's reputation as a competent and diverse manager of unusual projects.
Chapter V

POST OFFICE SQUARE PARKING GARAGE

Case studies for the thesis research

The remaining case studies described in this thesis pertain directly to the thesis research. They are intended to further investigate the project-oriented approach to technology found in the research recounted in Chapter IV. The reason for concentrating on the project-oriented approach is that it appeared to be the approach used for acquisition of technology that could more properly be considered construction technology: technologies employed in constructing facilities. The market-oriented approach, from the indications provided by the short research project already described, seemed to be employed in the acquisition of technologies pertaining not so much to the construction of the facilities as to the processes taking place within the constructed facilities. The remaining case studies
investigate the extent of the project-oriented approach to technology in construction and contribute to the understanding of this approach in terms of context-dependent knowledge.

The first of these case studies is the Post Office Square parking garage. It was conducted as a "pilot study", a study intended to identify the important elements in an innovative heavy construction project.

Description of Post Office Square project

The pilot study was conducted as a case study of the Post Office Square (POS) parking garage in downtown Boston. The $80 million project includes seven levels of underground parking and a public park on the surface. The 1.7 acre site is bounded by Milk Street on the north, Pearl Street on the east, Franklin Street on the south and Congress Street on the west. The study was begun in June of 1990 at which time the project was well underway (the seventh level was under excavation). The parking facility, which provides 1400 spaces, was completed and opened to the public in October of 1990 and the park area is expected to be finished in the spring of 1991.

This project is unusual from a technical point of view because it is the deepest structure in New England. It is
also the fourth use of the top/down construction method in Boston. The combination of the depth of the facility and the relative newness of the construction method make this project a challenging one. It is also unique in that it is an instance of "privatized" construction of a public facility where the owner is actually a group of private companies called Friends of Post Office Square (FPOS). FPOS bought the property (occupied at the time by a three-story, above-ground public parking garage) and will own it until their investment is regained (approximately 40 years) at which time the facility will go back to the City of Boston.

Top/down construction

The main technology of interest in this project is the "top/down" construction method, also known as up/down construction or the Milan method. It was developed in 1950 for the construction of the Milan subway. It was subsequently used for building construction where it allows for the simultaneous construction of the substructure and the superstructure.

The first step in top/down is the construction of a slurry wall that forms the perimeter of the foundation. A slurry wall is constructed by digging a deep trench that is filled with a bentonite slurry to stabilized the sides of the trench. Then concrete is pumped in, displacing the slurry
and forming a permanent wall. After this, foundation elements (piles, caissons) are installed within this perimeter wall. Then the top surface is formed, leaving an opening through which the excavation takes place. Through this opening each successive level is excavated, much like a tunnel. When a level is completely excavated a floor is poured which acts as a diaphragm providing lateral support for the perimeter wall. The next level is excavated under this floor and another floor is placed. This process continues through successive layers with each floor acting as lateral support between the perimeter wall and the foundation elements (see Figure 3).

Essentially, top/down construction is a method of excavation that eliminates the large hole produced by conventional excavation and the need for temporary supports for the walls of the excavation since the final structural elements (floors) provide support as excavation continues. The absence of a huge hole on the site is an advantage for construction in congested areas because the surface of the site itself can hold trucks, equipment, supplies, etc. rather than having those things tie up busy streets or be stored in areas off-site. Having the final structure provide support as construction proceeds makes deeper excavations possible without a need for obstructive cross-bracing or a very large number of tie-backs. In the case of building construction, the superstructure can rise as the substructure descends,
Up/Down Construction Process - Major Subsystems

Source: Becker and Haley
with the load above ground increasing precisely as the support below ground increases. Needless to say, this can save months of construction time.

In the case of the Post Office Square garage no building is rising above the garage. Rather, a public park is being developed above the parking facility. The advantages of top/down in this project included: enabling a deeper facility to be built without a tremendous number of tie-backs into adjacent property to support a conventional excavation and avoidance of traffic problems since equipment could operate from within the perimeter of the site.

Two things about this top/down technology should be recognized from the outset. First, it is an example of an innovative construction method or process and involves no "new" products. As such, it may not provide much insight into the development of innovative construction products but could be a very good example of "pure" process innovation. All of the constituent products and methods were preexisting; it is their sequence and coordination that is new. Second, it is a subsurface or geotechnical innovation. Foundations are a particularly crucial and risky area of construction and the process of development of technologies in this area may not be reflective of construction process development in general.
Results

The original intent of this pilot study was to trace the paths of communication about new technologies on a heavy construction project. The data was to be gathered by means of personal interviews. In the process of these interviews though, it turned out to be rather difficult to fulfill the original purpose of the pilot study precisely. The main reason for this seemed to be the absence of a vocabulary to discuss technological development and the communication of knowledge in construction. This would indicate a certain absence of formal concepts of these things, though not necessarily an absence of development and communication of technology themselves. These are just not the kinds of things many people in the industry analyze explicitly.

When words like "innovation", "research" or "development" were used in the the interview questions, the response was almost always negative: these things "don't happen" in construction. In several interviews it arose that construction professionals often do not consider new things to be new until someone else points it out to them (3.6, 9.4)\(^1\). In one case someone on the POS project (POS-SV 2) dismissed the idea that something new had been implemented in the forming of the garage floors although someone else on the

---

\(^1\) See Appendix for key to interview citations.
project had stated that it was an innovative detail on the part of the contractor (5.13). Whether this is because the developments are so incremental that they seem to those close to them like logical extensions of existing methods and therefore not "innovative" or that builders instinctively deny innovation because they do not want to appear to be taking undue risks on an owner's project or that "newness" of technology is simply not an important issue and therefore not considered, remains to be discussed. Any of these explanations implies an interesting concept of "innovation" or technological development.

The following paragraphs contain the specific topics that arose in the Post Office Square (POS) project arranged according to major topics and some comments on each one.

Communication

Under the general theme of communication several topics arose. Brief descriptions of these topics and some of the comments offered concerning them follow:

Communication in the industry in general. On one hand interviewees thought that communication in the construction industry is very poor (4.10). In particular, it was mentioned several times that innovations often come from Europe and that it takes a very long time for these...
innovations to reach the U.S., typically 30 years (11.11, 4.11, 7.11, 6.9). Another indication of poor communication that was mentioned occurs specifically on the project level but affects the communication of technological information throughout the industry and that is the absence of the constructor's knowledge at the design stage in most projects. The absence of construction (or "constructability") knowledge at this early stage precludes the introduction of any construction technology that would affect the design (2.7, 8). At the same time the lack of interaction between the designer and the constructor can cause the designer to be more conservative if he cannot coordinate his new design ideas with the builder who will implement them (6.22). The presence of coordination between owner, designers and builder from almost the beginning of the project was cited as a great advantage by interviewees from the POS project (5.16, 7.7).

On the other hand, information appears to be quite available. For instance, of the four projects in Boston that have utilized top/down construction, the contractors on three of them were using it for the first time. Apparently it was not difficult for each to learn what was necessary to use this method. When asked where they get information about technology, the answers from POS participants included: trade journals, conferences, manufacturers and suppliers, travel to sites, colleagues (1.1; 3.3,4; 4.12,13; 6.10,27,31). In one case (6.31) it was explicitly indicated
that there is a free flow of knowledge regarding experience gained on projects: this particular firm had no difficulty receiving or transmitting helpful knowledge gained from using a new technology.

**Communication within firms.** Industry executives mentioned that it can even be difficult to get information transmitted between parties in the same firm. Divisions within the firms may act as if they were separate, even competitive, companies (9.3). One analyst (12.7) confirmed the existence of this difficulty and attributed it directly to knowledge in construction being very much contained in the "experienced person" and to the project nature of construction where these experienced persons are moved from project to project.

On the positive side, several firms have taken practical steps to remedy the communication difficulties within their companies. Some have set up offices of "research and development" or "technical services" the primary purpose of which is to keep track of the developments in technology (sometimes both within and outside of the firm) and to communicate this information to those within the firm who may need it (CCRE p.13, 9.4, 10.2, 8.6). In particular, to make that knowledge which already resides in the firm more easily available to others within the firm, several companies have compiled lists of "in-house experts" that can be consulted by
anyone looking for expertise with a particular technology or type of project (6.12, 10.10, 9.5).

"Visual" presentation of information. A few comments were made that seem to relate to a "visual" aspect of knowledge. They may be minor but they seem to point to something. The first was a set of comments by a the project engineer for POS. First he indicated the need for drawings or sketches whenever a change needs to be communicated to the field. The new instructions must be written to be official but a new drawing is still necessary otherwise the people in the field are likely to fall back on the original drawing (2.2). He also mentioned that he has perceived a decline in the quality of drawings during his 16 years of experience in the industry (2.6) and a decline in the constructability of designs (2.4), both of which he associates with the use of computer aided drafting (CAD). Another comment came from an analyst who mentioned that an example of a technology which she thought was very good is Bechtel's "walk-through" program (11.8). This is a computer program that allows the viewer to feel as if he or she is walking through the completed constructed facility by presenting a moving "3-dimensional" image of the facility from the perspective of a person walking through it — essentially a simulated tour of a facility which can take place before the construction has even begun. This example was striking because the technology in itself does not seem to add substantively to either design
or construction but is more of a visual tool, more helpful, one might expect, to a non-technical person than to someone trained to read two-dimensional drawings of 3-D facilities.

**Experience.** The issue of professional experience came up many times. Both a senior consultant (4.9) and the geotechnical firm (6.31a) felt that the primary thing they had to offer to a client or a project was their technical experience rather than products, processes and more than formal knowledge even though these are certainly important. In the geotechnical firm even the principals of the firm maintain technical involvement through specific projects.

From the comments of two interviewees it appears that the specific contribution of experience is, logically, to the actual execution of a project, that which requires specifically practical judgments. One consultant said that judgments should be "tempered by a wide range of experiences." He believes that while some think that experience makes one narrow, it is actually necessary to be able to look beyond today and to *imagine* what might happen (4.9). This could be linked to the previous section on visual presentation: experience provides one with an internal portfolio of actual scenarios stored in the memory and able to be retrieved and manipulated by the imagination, a sort of interior simulation program. The influence that experience has on practical judgment causes the approach to a
project to differ based on the experience of the person involved. Some elements of construction are well-defined, "formalized": there are certain acceptable ways to excavate, certain acceptable ways to do formwork, etc. But the way a problem is approached, and implemented in detail, depends on experience (2.11).

To summarize this subsection about communication briefly: It appears that communication in construction is poor in the sense that information about new technologies does not spread quickly, apparently because the industry and even individual firms are so fragmented. This fragmentation is related to the importance of experience as a form of knowledge: individuals are working on projects separated from each other in time, place and even organizational structure of the firm. In the absence of formal means of communication that overcome these barriers, people must learn from personal experience. Some companies are trying to institute such formal means of communication. On the other hand it could also be that knowledge about construction (or certain kinds of construction knowledge) are simply difficult to communicate through formal means so fragmentation is somewhat inevitable and the reliance on experience is the rational solution to this. There is also a suggestion that a "visual" aspect of knowledge may be important to construction. If this is so, the acquisition of experience may be important in construction for the development of a
personal store of visualizable situations that can form a sort of internal simulation of projects and scenarios that would be too large, expensive and time consuming to build models of to provide external scenarios. There are technologies, though, that could aid in this area. Last, but very much related to the above points, the importance of experience seems to be directly related to the practical judgment that must be made in the execution of a project.

Role of the project

Harold Forsen, Senior Vice President and Manager of Research and Development for Bechtel Corporation, says that "construction managers have to be the most innovative people, because they work on-site and in real time, and every site is unique" (CCRE p.10). Throughout the case study and the other interviews the idea of the project as the locus or occasion for learning about and developing technology came up frequently. The project-driven nature of innovation in construction has been discussed by Tatum (1987). Responses from the interviewees shed some light on what appears to be a two-fold role the project plays: project as classroom and project as laboratory.

Project as classroom. The construction project is the location of much learning in the industry. Industry professionals look to projects that have already occurred or
are in progress to learn about the success of new technologies. They look at actual projects because they are not just interested in knowing that a technology exists but that it works. This can be learned through the means of communication mentioned above: professional magazines, conferences, etc.

Projects that one is actually working on also become opportunities for learning about technologies. Professionals at one firm said that from working on Boston's top/down construction projects they learned more about top/down, slurry wall construction and a foundation called a load bearing member or LBM (6.3,19); although each project was using the top/down method the variations among the projects led to the use of different foundation elements. Even with respect to top/down itself, no one on the project, not even the geotechnical engineers, "invested" in learning about the technology prior to use. They learned about it when a specific project looked like it could use it (6.8). Their learning increased from project to project (5.16). One consultant said he learned about top/down through the mistakes that occurred while he worked on Rowes Wharf (4.4).

A series of actual projects is also a classroom for learning engineering judgment. One geotechnical consultant explained that the analysis of the soil-structure interaction that must be performed on such projects is done using a
finite element program developed for this purpose. But the program requires the input of soil variables which are matters of engineering judgment. He indicated that the judgment of the adequacy of these variables comes from experience (6.5). Another geotechnical consultant confirmed that the predictions of soil movement in the POS project were derived from experience on previous jobs (7.19). In fact, none of the "models" that the geotechnical consultants were using to make estimates had the precise characteristics of the POS project; usually these are not known until one is already in the thick of the project itself, so estimates must be based on engineering judgment developed through previous experience.

**Project as laboratory.** The project also turns out to be a "laboratory" for the development of construction technologies. This development is primarily through incremental improvements to existing technologies, perhaps usually process technologies. The series of projects in Boston using top/down construction illustrates this development well. At the time that the POS garage was first conceived, in 1982, from 1 to 4 subsurface levels were being considered with 4 levels really stretching the envelope at that time. Since then Rowes Wharf, 75 State Street and 125 Summer Street were built with each one going deeper or perfecting the process more so that by 1988 seven levels were possible for POS (6.1,2). Even with the top/down method
having been used in these projects it was still necessary to 
work on it more. On POS they had to work out the details of 
the sequencing of operations. It took several levels of 
excavation and pouring before they got the sequence down to a 
production system with the kind of efficiency they had 
planned with at the beginning (7.10).

One particular area of progressive improvement was the 
forming procedure for the below grade floors. Earlier 
projects had formed the slabs on grade or with forms 
supported from below. As these were not found to be 
satisfactory, the contractor on POS formed the floors using a 
Strickland forming system with a different supporting detail. 
The forms were suspended from above, from the columns that 
had been installed immediately after the slurry wall was 
constructed (POS-SV.2). This new procedure took some effort 
to be perfected. Several failures occurred with the forms 
because of failed brackets until a whole new set of brackets 
had to be purchased (7.10).

Two other industry professionals interviewed indicated 
that they also found small improvements, particularly in 
processes or procedures, occurring on job sites. One person 
said that most problems that get solved on the project are 
geotechnical because "surprises usually occur in the ground" 
(10.12). He said his firm did not have any method of 
gathering information about such incremental developments.
The other interviewee noticed this problem-solving sort of development during her own project experience and has more recently begun to gather information about this so that knowledge about improvements can be communicated to others in her firm who may encounter the same problems (9.3,4).

There was some indication in one interview (7.18) that one designer on POS may have had to do some "implementation-type work" on a new soils analysis program, developed by others, to make it useable. This question has not been pursued.

Besides incremental improvements, other forms of development and "research" are sometimes performed on individual projects. Sometimes a technology must be used for which there are still some fairly well-defined questions unanswered. In such cases a small test program may be carried out on the project site. One interviewee provided an example of a building project using high-strength concrete. The technology for patching voids and unevenness for this concrete was not developed so the contractor carried out a small on-site program in which voids were caused and then repaired to pass inspection (10.14). One of the geotechnical engineers also indicated that they perform on-site test programs when they are going to do something very unique (6.27c). A specific example of such a program by this firm occurred on the Hynes Auditorium project. That project used
mini-piles of a diameter and capacity never used before in
the U.S. under the conditions present, so a test pile program
was performed before the preparation of the contract
documents to demonstrate the feasibility of the proposed
procedure (Johnson and Schoenwolf).

Several persons mentioned the use of monitoring programs
to gather performance data on individual projects. Rowes
Wharf and POS are good examples of this. On Rowes Wharf the
gеotechnical engineer monitored the slurry wall in every
possible way to gain knowledge about the behavior of such a
structure (6.23). POS had an extremely extensive
gеotechnical monitoring system that measured and evaluated
wall movement, soil movement, ground and building settlement
and groundwater levels (7.6,13). Another example involves a
building in Cleveland in which the contractor installed a
monitoring system to monitor the creep and shortening of
high-strength concrete. The interviewee referred to this as
using "the project as a lab" (10.5).

All of the examples in the previous two paragraphs
involved testing or monitoring programs that were part of
specific projects and the costs of which were passed on to
the owner of the facility under construction. In each case
this could be justified as being a service the owner needed
since his facility was unique and would need extra testing
and monitoring to insure success. From the point of view of
the engineers and constructors, these project-specific programs do have significance beyond the specific project. They provide data and experience that will influence engineering judgment in design and construction of future projects. And if they are part of an overall plan to learn more about soils, concrete creepage, etc. these data can be analyzed and help to develop more formal or scientific understandings of engineering structures or their environment. There were two indications in the interviews of more systematic non-project-specific attempts to gather knowledge about the behavior of engineering structures. One interviewee said his firm was considering developing a computer program to analyze concrete creepage if such a program did not already exist (10.6). He clearly indicated that this was not a project-specific endeavor. Another stated that they themselves paid to have monitors put in the piles of buildings so that they could gather performance data over time (6.24). Perhaps this could also be referred to as using the site as a "lab."

There was some indication in the interviews that it was the specific demands or constraints of particular projects that "caused" or created the innovations in construction. This recalls the Forsen quote given earlier that related a construction manager's innovativeness to the uniqueness of construction projects. For instance, unique constraints encountered in the Hynes Auditorium project (limited headroom
for driving piles, existing subway and turnpike rights-of-way beneath the site, and the requirement of large column-free spaces in the auditorium) drove the engineers to use a type and configuration of piles that had not been used previously in this country (Johnson and Schoenwolf 1987; 6.11,26). In another project, 101 Arch Street, after several attempts at other foundation solutions, the engineers tried what would be the first successful totally endbearing slurry caisson (6.14). Two interviewees phrased this idea of project constraints driving the innovation as one of "logic": given all the requirements and constraints there seemed to be no other logical choice but to do what turned out to be innovative. "Innovation" was the result of necessity, not explicit intent (3.5, 6.11).

Other project related issues. It should also be noted that one interviewee did agree that the technological approach taken in POS was largely due to the "constraints" of the project, but he hastened to add that these constraints did not seem to be unique. They were the typical constraints one would find in urban construction: close neighbors, busy streets, no space to maneuver or store things, etc. (7.4). Also, another possible "cause" of innovation in construction was proposed in one interview; that is risk reduction. One geotechnical engineer posed site constraints and reduction of risk as two alternative causes of innovation (6.26). Hynes Auditorium would be a case of innovation due to site
constraints, but he thought 75 State Street's use of top/down was a question of reduction of cost and risk (6.28). Top/down separated the risk of the upper portion of the building from the risk of the subsurface portion: if there were problems digging down, fewer subsurface parking levels could be built but the developer would still get a building to rent out, on time (6.16). This same engineer said that top/down was used on POS to reduce risk because the method had proven successful on three previous projects. This would corroborate the statement mentioned above that it was not uniqueness of site constraints that prompted the use of the top/down method.

So it looks as if there could be at least these two ways that specific projects "attract" innovation: the project's constraints make the innovation the "logical" or perhaps the only technically feasible solution; or several solutions could be offered technically but a newer technology actually minimizes the risk. This latter possibility would imply that more "conventional" methods in some cases would actually entail more risk than a new technology. Might this not be precisely when a project pushes the state of the art?

Another comment on the project-specific nature of technological development in construction came from one of the industry experts. She acknowledged that the acquisition or development of technology is often driven in a project-
specific manner but this does not mean that there are not generic problems which are currently being addressed by multiple parties simultaneously but separately (11.4). She thought that people may not get out of their own technical specialties far enough to do the "environmental scanning" necessary to see that their particular problems are actually shared by others and perhaps even being successfully addressed by others (11.3). As was presented under the section on communication, this is a problem that some companies have recognized and have tried to address through creating positions for people who will do the environmental scanning for the company or through compiling lists of in-house and outside experts for consultation. She related a story of an American Consulting Engineers Council (ACEC) awards meeting where a winning project involved installing bridge segments without obstructing a waterway. It was this feature of the project that its designers considered most innovative. A U.S. Army general involved with waterways also attended the meeting and admitted that this was a problem he had to deal with as well (11.5). Another example of a more generic problem is dangerous or hazardous construction environments: robots could be developed for use in such places (11.6).
Importance of process

Another recurring idea in the interviews is the importance of "process" in construction. Several interviewees indicated that their concern as builders is more centered on the procedure or process than on products. The input of the contractor, according to the project engineer on POS, is mainly to the efficiency of construction. While a designer may try to minimize material cost, for instance, the contractor is concerned about the process cost which will include the labor and equipment and the very feasibility of accomplishing a design — the constructability of the design (2.3). When a superintendent plans out a project he concentrates on the operations involved, weighing the availability and efficiency of various pieces of equipment. Sometimes he will decide to purchase new equipment, but often he is willing to "struggle along" with a less than ideal piece of equipment though it may "seem" less efficient (2.14) but the overall cost is less.

The concentration on construction procedure seems to influence what types of technologies get developed where. One interviewee acknowledged that what may be considered their "in-house development" always involves the development of on-site procedures using products that are already available on the market (8.1,5) or learning about something and figuring out a way of doing it themselves (8.3). Usually
their first approach would be to subcontract such work but sometimes they will do it themselves (8.2). (This respondent was not sure why one approach would be used in some circumstances and one in others.) The same respondent stated that the construction technology that is developed day-to-day on the job is "not worth publicizing" (8.8). An engineer on the POS project also stated that top/down construction is basically standard construction operations put together differently (6.18). So the innovation is in the procedure as a whole. Another POS participant pointed out that the role of the designer and the contractor on the project were precisely to handle the challenge of executing the method (3.4).

Two interviewees also mentioned the importance of the process going on inside the facility in the case of process plants. One thought the important technology for competitiveness is engineering process technology. His company learns the clients' processes and figures out how to do them better (8.8). The other individual confirmed the importance of engineering process technology when he said that industrial construction is becoming more process-driven (CCRE p.13). This area is not traditionally considered part of "construction" but is apparently crucial in industrial construction. This may not apply to other kinds of construction.
An industry expert suggested that the research concentrate on construction processes because it seems that it is the processes or techniques that actually originate within the industry whereas construction product technologies seem to come from without, from manufacturing (11.14). When asked what major improvements in construction technology originated in the States she suggested that any combination of laser technology and a construction operation seems to have been developed here: laser cutting, laser guided paving, the use of lasers in measuring or surveying, etc. (11.13). This would be the improvement of an operation which is then embodied in a product. An example of such an innovation is the partial automation of grading equipment using a laser alignment system (Tatum 1988). This innovation involved the cooperative efforts of a grading contractor and a laser system supplier.

Role of participants in project

Part of the objective of the pilot study included determining the roles of the various project participants in communicating about technology. This section compiles the comments that interviewees made about their own or other participants' roles in the POS project or in construction projects in general.

The major participants in the POS project were:
Owner: Friends of Post Office Square, Inc., a group of Boston’s civic and business leaders. Members of Friends of Post Office Square are: Bank of Boston; The Beacon Companies; The Beal Companies; Cabot, Cabot & Forbes; Cabot Corporation; The Druker Company; Eaton Vance; Equitable Real Estate; Fidelity; Hamlen, Collier & Company; Harvard Community Health Plan; Hexalon; Leggat McCall; Meredith & Grew; New England Telephone; Nordblom Company; Olympia & York; Richard H. Rubin; Shawmut Bank; State Street Bank.

Owner’s geotechnical engineers: Haley and Aldrich

Owner’s construction consultant: Roy Stifler

Design Team:

Lead designer: Parsons Brinckerhoff Quade & Douglas, Inc.
Structural engineer: Le Messurier Consultants
Mechanical and electrical: Cosentini Associates
Architectural: Ellenzweig Associates

Contractors:

General Contractor: J.F. White Contracting Company
Slurry Wall contractor: ICOS of America
Owner. The representative of Friends of Post Office Square who was interviewed stated that he (his firm) was responsible for the decision to use top/down construction on the Post Office Square project (3.2). His firm had brought top/down construction to Boston, using it for the first time on the Rowes Wharf complex and then on 75 State Street. So they had knowledge of the method and first hand experience which brought the method to mind for the POS project and gave them the confidence that it could be effectively used to build a very deep parking garage. This interviewee's firm had learned of top/down from two sources in connection with the Rowes Wharf project: the architect on Rowes Wharf had worked on a project in Chicago that had used top/down so they suggested it for Rowes, and one of the contractors, a European firm, who bid the Rowes Wharf job suggested it (3.3A). This contractor did not win the job though.

This interviewee felt that the lead designer on POS had "at best a marginal role" in bringing top/down into Boston and that the general contractor played no role in its introduction (3.3). Rather, he saw the role of the designer and the contractor as one of meeting the "challenge of executing the method" (3.4).

Designer. Only a representative of the "lead" designer was interviewed. He said his company was involved with the POS project since about August 1987. The firm assessed the
constructability of alternative construction methods from the
design point of view. From their own experience and
knowledge of the soil the designers knew they had to use
slurry wall construction. Their analysis of constructability
in this case involved explaining why this was the best method
and determining how to excavate within the slurry wall and
how to support the walls of the excavation (5.4). This
involved development of a "baseline scheme" against which
other excavation alternatives could be compared with respect
to things like time and cost (5.3). The baseline scheme has
to be a feasible, positive method of construction. For the
POS project this method was flat plate (referring to the
floor structure) top/down construction precisely because of
the experience that the above-mentioned representative of the
owner had had with it. This was the method with the greatest
number of "knowns" so it represented the most "certain"
approach for such an innovative project (such a deep
excavation in New England) (5.6). The contractor was not
involved, according to this interviewee, until about eight or
nine months into the design.

This representative of the lead designer described his
firm as responsible for traffic, site work, utilities,
overall management and construction, constructability and
cost (5.8). During construction they served as the project
manager for the design team (5.12). He stated that his firm
was chosen to be the lead designer because of their
experience in heavy underground civil projects. He described the necessary knowledge and capabilities of such a designer as follows: he must know that what he is designing can be built; he must be sure he will not damage other buildings; he must be able to assess the risks and various factors beforehand and be able to incorporate these clearly in the contract so the contractor will be more confident and give a lower bid without a lot of padding for contingencies (5.9). These requirements mean that the designer must know a lot about construction, but it is difficult for him to keep up with everything so he needs help: in-house construction experience from other designers who have been around longer and hiring construction consultants. For the POS project the lead designer hired a consultant, Rubin Samuels, to review their design. They also had access to Roy Stifler, the owner's construction consultant (5.10).

The designer's previous exposure to top/down construction included some work on Rowes Wharf and the use of the Milan method (the name top/down usually goes by when it is used for tunneling) for a small portion of the Harvard Square subway station (5.11).

Contractor. The major responsibility of the contractor is the efficiency of construction (2.3). Project management is the focus of a contractor and technologies are only valued inasmuch as they contribute to management as tools for
monitoring the work, procuring supplies, controlling inventory, etc. (CCRE p.12). With respect to new construction technologies to be used on the project, the general idea of the role of the contractor, from interviews with several contractors, is basically that the contractor should "keep himself abreast of" recent developments. The project manager on POS listed the magazines, conferences, trips and conversations with manufacturers that he makes use of to know what is being developed and successfully used (1.1). Other construction industry personnel expressed similar methods and special offices set up in their companies to keep up to date on technologies, as mentioned earlier (10.2, 8.6). The one criticism given to contractors was not that they do not do formal research and development themselves but that some of them are not inquisitive enough, they do not read so they can find out about new products and methods (4.13).

One interviewee, a geotechnical engineer, said that he sometimes speaks to contractors to keep up with what they are doing but he thinks that in Europe, where there is a greater tendency toward design-build projects, the builder has more influence on technology. Here, he said, the technology is more pushed by the design (6.13).

Geotechnical engineer. Since the POS project relied so heavily on geotechnical engineers it is appropriate to
consider their role separately even though it is not wholly distinct from the design role. There were several geotechnical engineering firms affiliated with the POS project. The owner had their own consultant (Haley and Aldrich), which is unusual for an owner (7.6). The designer has in-house geotechnical expertise and hired a consultant (Rubin Samuels). The contractor had a consultant (GEI). The City of Boston requires a review engineer (Mueser Rutledge) who was apparently also an advisor, later in the project, to the diaphragm wall contractor (6.7, 7.8). Then there were the geotechnical engineers on the owner's geotechnical monitoring committee which will be discussed under consultants and advisors. Apparently, all these engineers worked well together to address any questions or problems on the project (7.7).

The role of the geotechnical engineers on POS was to help the design team understand the "soil/structure interaction": dewatering, stability of the excavation, soil pressures as the structure descends, etc. The various geotechnical engineers used a finite element program to model this soil/structure interaction, but the crucial element was the judgment of what values to use for soil variables. Then these engineers would design a solution for the situation as modeled and analyzed, working with the design team in an interactive process (6.5).
With respect to new technologies, geotechnical engineers seem to keep themselves aware of developments in much the same way as contractors: through professional literature, conferences, colleagues, etc. (6.27). One interviewee said that he thought if the geotechnical engineer were involved earlier in the design of a project he would be in a position to suggest the new things of which he has become aware. He said that in the past there was a tendency for the geotechnical engineer to be brought into a job after the major decisions had been made (7.12). Clearly this was not the case on POS where the owner dealt with a geotechnical engineer from the beginning of the project. This geotechnical firm is the one that had been involved in every top/down project in Boston—the "reigning experts" (3.10)—and was then free to influence technology-related decisions from the beginning.

**Consultants/advisors.** Two individuals were interviewed who filled the role of consultant or advisor on the project rather than being one of the conventional construction participants (owner, designer, contractor). One was hired by the owner because of his 35 years of experience in construction (4.4) to advise mostly during the preconstruction phase. He studied alternative methods and tested them by making and comparing estimates of advantages, disadvantages, costs, safety, schedule, environmental impact, etc. Describing his role as one of "devil's advocate", he
said it required experience and imagination to be able to conceive of other feasible methods to test and challenge those under consideration (4.5). During construction he monitored the activities of others—designers and contractors—with respect to construction and geotechnical monitoring (4.6). He described his role as more active at the beginning and less so during construction when he acted more as an observer and critic, "like an insurance policy" (4.8).

The second advisor was an MIT professor, a geotechnical engineer, who served on two of the owner’s committees. The first was the Technical Advisory Committee which dealt with questions of design, construction and operation of the garage. This committee met about once every two weeks. They recommended the designer, contractor, operation plan of the garage and the use of top/down construction to the owner (7.2). Once the project was underway this professor chaired the Geotechnical Monitoring Committee. This committee constantly reviewed the data gathered in the geotechnical monitoring program (slurry wall movement, building movement, etc.) and reported the results regularly (7.5).

To summarize this section, the immediate source of the idea of using top/down construction at Post Office Square was the owner, due to the previous experience that one member of Friends of Post Office Square had with the method. The
technical expertise with the method seemed to lie more with the geotechnical engineer hired by the owner due to their experience with the method on three previous Boston projects. The consultants (and to some extent the designer) played the role of analyzing and comparing the top/down methods with other alternatives so that the method would not necessarily be used just because the owner was familiar with it and the owner's geotechnical engineer had more or less "cornered the market" on expertise with the method. As far as being a source of knowledge about or a party to the decision to use the top/down method, the contractor was not involved. His role was simply to learn about and execute as efficiently as possible the details of the method. This whole scenario may not be typical. As one person mentioned, geotechnical engineers are not always involved early enough in a project to bring new ideas and expertise to bear on the design. It is also not so common for an owner to engage so many consultants independent of the designer and builder. These consultants could provide design, construction and operation advise early enough to have a lot of influence on the technologies used. What does seem to be typical is the very minor role that the contractor has with respect to expertise and decision-making. This appears to have been the case with the other top/down projects in Boston and with other contractors who were interviewed.
Industry and firm issues

This section covers a variety of considerations made by the individuals interviewed that pertain to the structure or patterns of behavior in the construction industry. Much of what is here overlaps with previous sections but it is useful to consider some of these issues separately.

Sources of construction innovations. It is noteworthy that several people interviewed indicated that Europe is often the source of new technologies or adopts them more quickly than the U.S. One industry analyst said it typically takes about 30 years for construction innovations to get here from Europe (11.11). Three others commented on Europe being a more frequent innovator (7.4, 6.4) or adopter (4.15) of construction technologies. Two people also mentioned that construction products (equipment and materials) in the U.S. originate from outside the construction industry in manufacturing industries (10.8, 11.14).

Separation of design and construction. The U.S. construction industry is characterized by low vertical (and horizontal) integration (12.4). Even on individual projects the interaction between stages is very much minimized. Two people related the slowness in incorporating new technologies in construction to this compartmentalization of the design/construction process. One thought that contractors in
Europe may have more input with respect to construction technologies because there is a greater tendency there to integrate design and construction (6.13). In this same interview an engineer thought that contractors are beginning to get more involved at the design stage in "deep" construction projects. As mentioned earlier one interviewee thought that geotechnical engineers would be able to make a greater impact on the selection of new technologies if they were more habitually involved with early stages of design (7.12).

**Private vs public ownership.** The issue of integration of design and construction is related to another issue which is private vs public ownership of projects. The engineer cited in the previous paragraph concerning the involvement of contractors in the design stage of "deep" construction qualified his statement saying that such interaction only occurs on private jobs (6.22). When asked if the success of the POS project was due to its being privately owned, one engineer said he was not sure if private ownership was the specific cause of success, but that one good thing about having a private owner is that you can get decisions made more quickly because someone with authority is more available than is typically the case in public jobs (5.18). In addition, on public projects the budget is fixed and the money is public funding. There is no incentive to save time or money, just to get the job done on budget. Private
owners, on the other hand, use their own money or borrow so a shorter construction time saves money in interest on loans and allows the owner to generate revenues sooner. This creates an incentive to spend more on technologies to get the job done faster because this money is an investment that will pay off (5.19). Another engineer mentioned that designers tend to be more conservative when designing for public agencies. Due to the separation between design and construction in public work, the designer has not been able to coordinate with the builder and may not be able to do so once construction begins. So the designer must be sure his design is simple, clear and standard—not in need of any interpretation (6.22).

How firms view the role of technology. One respondent said that the most important thing to look at with respect to technology is market advantage because the construction industry is completely market driven (3.1). Another elaborated and said that the important considerations in deciding about technologies to use are cost, risk and technical feasibility, in that order. Despite this order of priority, in practice one considers them in the reverse order, he said (6.15).

One industry executive, interviewed for the CCRE newsletter, spoke of the importance of technology as a strategic element. The technology he speaks of is that which
his clients require for the processes they run within the constructed facilities. What is interesting, though, is that his firm’s attitude toward these technologies is very much like the attitude of other firms toward construction technologies: it is not important to develop the technologies but to keep abreast of them and know how to use them efficiently:

R&D has a key strategic management role. Bechtel can use its talent on behalf of a client and evaluate the tradeoffs, perform the technology evaluation, feasibility studies, and conceptual designs up front before people go forward with projects. We can monitor what technology is available, what the economics are or should be, and perhaps propose a more optimal approach for the clients to undertake. This puts us in a couple of places. It puts us well abreast of the development of technology, but it also puts us in a position to carry out the work. (CCRE p.13)

With respect to research agenda:

Our most important task is to be sure we are communicating internally. We must insure that our talent base complements our other internal resources when new technology is involved. We don’t want our internal clients seeing technology-driven activities on which we’re not up to speed through their external clients. (CCRE p.13)

Another executive, also from a firm that builds process plants, spoke of the importance of knowing about and perfecting the details of clients’ process technologies (8.8).
One builder commented on the strategic advantages and disadvantages of having more knowledge about a particular kind of project due to experience. Generally, he said, the knowledge you have about a project (its environment, for instance) rather than the equipment or techniques per se, is a competitive advantage. Equipment does not pose much of a competitive advantage because if someone else won a project requiring a piece of equipment only the interviewee's firm had, the firm would probably rent the equipment to them. When it is not being used it might as well be earning some money rather than sitting idle (2.16). On the other hand, he observed, sometimes knowing the "inside" scoop on a project—because you've been on the site previously, for instance—is a disadvantage in bidding. You include a lot of hidden expenses you know about so your bid comes in higher. Another bidder, not knowing of these expenses, will bid lower and get the job although he will make less money. When the interviewee's firm was bidding for a similar job they did keep other people off the POS site because they did feel that their knowledge from this project gave them a competitive edge. Even at that, the interviewee was not certain that this was necessary or even good. Maybe they should have let other bidders on the job so they would have seen the pitfalls and included them in their own bids.

**Analysis of the construction industry.** To end this section some comments from one industry analyst are
presented. First, he says that the industry as a whole is not deficient in innovation; we just do not know how to measure it (12.2). Second, he thinks the age of the industry is part of the difficulty—it is easy to be innovative when your industry is relatively new and was sparked by new discoveries and inventions. Construction is very old and needs to look at new things like biotechnology, electronics and advanced thermodynamics to find an impetus for new technologies (12.3). He also sees an analogy between Japan after World War II and the U.S. after the Civil War: in both cases the countries had to rebuild, to start from scratch, so there was in each case a “frontier” that created a demand for investment and reconstruction (12.5). He proposed two possible scenarios to overcome this difficulty for innovation in construction (12.6). He called the first “economic Darwinism”: a decrease in the number of firms with the emergence of fewer, larger firms that branch out into various areas. There would be less dependence on local situations because if demand for construction drops in one place the firms do more work elsewhere. The second scenario involves continuing with a highly disaggregated industry but with enhanced management technology and pressure to keep capital down. Firms would become increasingly specialized and a brokerage system would develop in which equipment, etc., are available to all. The first scenario seems to be supported by a recent trend of labor moving to find work, and therefore less dependence on the local labor market; and a trend of
more uniformity of building codes, and therefore less dependence on local codes. On the other hand, the second scenario seems to describe the overall tendency of the construction industry. The "brokerage" approach to technology is almost the culture of the industry already. These issues will come up again in the analysis of the pilot study results.

**University/industry relationship**

Although it was not initially included in the plan of the interviews, the relationship between the design and construction industry and universities was commented on in earlier interviews. This led to the incorporation of the issue into a few of the later interviews. Note that most of the interviewees are design and construction professionals, two are industry researchers or analysts and only one is a university professor; so most of the comments are from the industry side of the university/industry relationship.

Most of the people interviewed were educated as engineers, usually civil engineers: Whitman (7.1), Stifler (4.14), Schoenwolf and Haley (6.32), Blouin (2.1). Thomas (10.18) and Cusson (9.2) were more specialized in building technology and management. Lemer, Abbott, Barlow, Harrison and Becker are all engineers, presumably civil engineers.
Only Ms. Page's university preparation is far removed from engineering; she has earned a graduate degree in English literature (11.1).

The professor interviewed described a growing gulf between university and practice in civil engineering. He said that there is a general feeling in industry that research has nothing to offer and on the other hand researchers often do have little motivation to do work that is related to general practice (7.15). Research is often related to very special problems that do not arise frequently enough to be of interest to more than a few members of industry (7.17). Part of the reason for this is that there is more research funding available for special problems and esoteric questions than for developments in areas of more general interest (7.15,17).

Two engineers described the gulf between industry and academia from their point of view by commenting on the irrelevancy of journal articles to their practice. One engineer said he simply stopped reading some of his journals (6.35). His colleague pointed out that journal articles are usually by university professors and tend to be laboratory-oriented or theoretical (6.29), whereas practicing engineers present papers at conferences (6.3). Such papers (by practicing engineers) are usually about experiences with particular projects.
The professor and these two engineers are all specialists in the field of geotechnical engineering so they are looking at the university and industry sides of the same subdiscipline in civil engineering. The professor described something of the history of change in the university/industry relationship in geotechnical engineering (7.14). When the field started there were very few geotechnical firms, maybe a dozen in the U.S. The papers and presentations at meetings of the American Society of Civil Engineers (ASCE) and the Boston Society of Civil Engineers Section of ASCE were all given by academics. Now there is a an enormous number of firms and most of the presentations given at these conferences are given by people in the field. At the beginning university research had very little influence on practice (researchers drew together basic principles and tried to explain them) but it passed out into the industry very quickly because the graduates were the ones staffing and even founding the firms. Now there is less interaction except when something big and new comes along and the industry feels it needs the university’s help.

It is interesting to note that one respondent compared the roles of industry and university research in the U.S. and in Japan. She said the university research in construction is better than the industry research in construction in this country. But in Japan, industry (companies’) research is
better than university research (11.7). She commented that in both cases the greater amount of research is performed where the government provides the incentive: whether funding to universities as in the U.S. or competitive advantages to firms as in Japan. Mr. Forsen, in his CCRE interview, also commented that in Japan industry does not interact much with the universities (CCRE p.11) but that is because the Japanese firms do the research themselves so they do not need as much interaction with universities beyond hiring young engineers.

Respondents did not only bemoan the gap between universities and industry; several thought the gap should be closed or narrowed and gave suggestions for accomplishing this. In general, the advice to universities is to include more exposure to practical engineering problems in both education and research. One respondent had graduated from the no longer existing "Course 17" at MIT, a course in building technology, which he felt was the best preparation for his position in industry (now a vice president at Turner Construction) because of its close ties to practical engineering (10.18). Another who went to MIT said the graduate theses that he and his classmates worked on were based on actual on-going civil engineering projects that their professors were involved with (6.33b). A third said professors and students at his university all spent time on consulting or summer jobs to gain experience that complemented their classroom and lab work (6.33a). None of
these comments reflected the slightest disdain for research or for theoretical work, but rather the need for both theory or analysis and practice for a richer, balanced education and more relevant research. One practicing engineer put it like this: nothing is more valuable than experience, but book learning gives you the logic for later problems (6.33b). Even the academician among those interviewed felt that younger professors are deprived of something valuable to their research when the structure of incentives they face leaves no room for "meaningful consulting" (7.15). Other comments directed toward universities included the need to find other means of funding besides research grants that propel them into more and more esoteric areas and away from the needs of the field (7.16) and the suggestion that students get more involved in environmental engineering (hazardous waste, soil contamination, site remediation) since there is great practical need as well as need for research in this area (6.34).

For industry, respondents suggested that they get more interested in and involved with what is going on in university research. Keeping up to date with university research is part of that "environmental scanning" mentioned by one analyst (11.3). An industry executive says he has identified eight universities with which he maintains contact to keep up with their activities and he is considering adding more schools to the list (10.11). Some suggested that
industry could get more actively involved with university research. First, industry must begin to recognize the benefits of research done collectively (7.16). One executive said industry should invest more time and money in university work (CCRE p.11). Even without this much involvement, companies can cooperate with university research by providing professors and students with opportunities for practical involvement through studying the companies' own projects (9.6).

Analysis of pilot study results

The data compiled from the Post Office Square case study fall along two major lines: 1) the fragmentation of knowledge about technologies in construction, accompanied by its availability, and 2) a need for contextual learning about technologies in construction. These two ideas are not independent of each other; in fact it seems that the need for contextual learning arises from the fragmentation of knowledge and that, vica versa, knowledge remains fragmented inasmuch as it is gained in a contextual way.

The first observation, the fragmentation of knowledge in construction, is supported by several findings from the pilot study. First are the interviewees' comments indicating that the Post Office Square project was unusual in its
incorporation of construction and more specialized
gеotechnical knowledge at the predesign and design stages.
Many projects are more compartmentalized with key conceptual
design decisions being made before certain engineering
disciplines are consulted and most, if not all, design completed before construction personnel are on the job.
Knowledge is also fragmented within the construction industry
itself where many companies may be trying to solve similar
problems simultaneously but separately. It is also
fragmented within construction firms where separate divisions
or project teams fail to effectively communicate useful
knowledge to each other.

While knowledge about construction and construction
technology is spread among various participants, interviewees
also indicated that such knowledge is fairly openly available
to those who look for it. Knowledge about equipment and
materials is available from suppliers and trade magazines.
Projects are described in trade and professional journals and
at conferences. In a way that appears to be similar to the
"know-how trading" identified in other industries (von Hippel
1988), know-how associated with using new products and
methods was described as readily available by one interviewee
(6.31).

What I have called "contextual learning" is also
prevalent in the pilot study data. The use of the project

114
site as a sort of "laboratory" for developing or improving technologies is the best example of contextual learning. Usually laboratories are precisely places where environment or "context" is controlled. A project site is not a controlled environment. But it is the environment, with all its variability and unpredictability, in which the technologies must actually perform. Another example of what is at least a perceived need for contextual learning is the emphasis that several interviewees place on linking civil engineering education to actual projects. Projects are also the context in which industry professionals are trained and the channels through which they learn about new technologies. There are some suggestions also of a need for visual representations and "simulation" of projects whether on paper, computer or in one's personal store of experience.

Both of the major ideas discussed (fragmentation/availability of knowledge and emphasis on contextual learning) pertain to knowledge utilized in the construction industry. Both suggest that knowledge in the industry is closely tied to practical circumstances and experience.
Chapter VI

NORTH STATION TRANSPORTATION IMPROVEMENTS PROJECT
AND JAMESTOWN VERRAZANO BRIDGE

Two projects were chosen to complete this research by further exploring the project- or context-oriented approach to technology in construction. These two case studies were intended to test and clarify the findings of the Post Office Square case study. Some of the issues which were explored at NSTIP and JVS were: the applicability of the conceptual framework in a different type of project, one not so heavily geotechnical in nature, for instance a bridge or highway project; the receptive role of the contractor in the introduction of new technology - could this attitude be picked up more strongly in the industry, how could it be related to the role of contextual knowledge; the availability of information about implementation of new technologies on projects - how widespread is this
availability, how, if at all, does it occur among contractors.

In general these two cases reinforce the results from the POS study but they also clarify these results and add some new insights into how technologies are developed and diffused in construction by means of contextual knowledge.

Description of North Station and Jamestown Bridge projects

The first project is the construction of a parking garage and subway tunnel which are part of the North Station Transportation Improvements Project (NSTIP) of the Massachusetts Bay Transportation Authority (MBTA). The project is in Boston, MA. The second project is the construction of the Jamestown Verrazano Bridge (JVB) linking Saunderstown, R.I. to Jamestown, R.I., a project under the Rhode Island Department of Transportation (RIDOT).

The parking garage and subway tunnel are part of a $300 million project to modernize the North Station facility with a new commuter rail terminal, platforms and tracks; a relocation of the Green Line from its elevated tracks; a new station with access to both Green and Orange Line trains; and a parking garage. The portion of this project which was studied for this research is the construction of a 5-level, 1300 car underground parking garage located beneath the
existing Boston Garden parking lot. This includes the construction of a part of the relocated Green Line which will pass through the second and third levels of the parking garage.

From a technological point of view this project is similar to Post Office Square in that it utilizes the top/down construction method (including slurry walls) but there are a few differences at North Station. First, it involves the first major use of polymer slurry (for the interior caissons) in the Boston area as a substitute for the more conventional bentonite clay slurry. It is also apparently the first use of the Formeze system for forming the floors of the parking garage. The North Station project also utilizes the super low ground pressure (SLGP) earthmoving equipment that was used on POS, a first for the North Station contractor and apparently only the second use for construction in this part of the country. Another unusual technology to be employed in this project is a track fastener which will isolate noise and vibration from the moving trains (passing through the garage). These fasteners will prevent vibration from being transferred to the tracks and eventually to the structural elements of the garage and the building (the new Boston Garden) which will eventually be built over the garage.
The second project is the Jamestown Verrazano Bridge in Rhode Island. This brand new bridge is immediately adjacent to and will replace the existing Jamestown Bridge crossing Narragansett Bay. The existing bridge has two 11 foot lanes. The new bridge, under construction, will be one and one half miles long and consist of two 46 foot roadways, a center barrier, two sidewalks, breakdown lanes and a bike way. It has a 600 foot free clearance, a 635 foot main span and is 135 feet above sea level at its main span.

The bridge is being constructed using a combination of cast-in-place and precast concrete techniques. The main span and the spans on either side of it are to be constructed by the balanced cantilever segmental method. In this technique segments of the bridge are constructed alternately on either side of a pier such that each new segment balances the previous segment built on the opposite side and in fact shifts the unbalance to its own side until, in its turn, it is balanced and “overcompensated for” by the next segment. Other portions of the bridge are being cast in place according to fairly conventional methods (like scaffolding supported on the ground). But the technologically unique part of this project is the precasting and lifting into place of concrete segments which are probably the heaviest lifts made above water in North America. The weight of these segments combined with the height of the lifts and the fact that they must be made from barges in rough water subject to
tidal fluctuations have presented several challenges to the contractors.

Major technologies

Polymer slurry.

Recall from the description of the top/down construction method that the use of a slurry in digging deep trenches and wells (perimeter walls, caissons, etc.) stabilizes the sides of these excavations. Often bentonite clay is used for such slurries because particles of the clay will interact with each other in the slurry to form a gel which is resistant to flow. Part of the stabilizing effect of this slurry is caused by its forming a "filter cake" against the surface of the excavation which helps prevent the loss of slurry into the surrounding soil or the infiltration of groundwater into the trench with subsequent failure of the excavation. The cake itself can hold individual grains of soil in place. A disadvantage of bentonite slurry is that it will tend to entrain particles of ground which will decrease its stabilizing effects. The presence of "desanding" equipment for removing these entrained particles combined with the large quantities of bentonite required to make the slurry require a fair amount of space, a disadvantage on cramped urban projects which are often the very ones using slurry wall methods (Beresford, et al.)
Polymer slurries, on the other hand, offer some advantages in the areas where bentonite falls short. A much smaller quantity of polymer is required for the same size job (1/10 to 1/40, Beresford, et al.). And more importantly, polymer slurries do not entrain much ground and therefore can be reused more often than bentonite slurries (8 times vs 2.5 times, Table 1). Some polymer slurries are also much easier to dispose of. A synthetic polymer used on the NS project is neutralized with bleach and is then fit for the storm sewer. Another polymer that is being proposed for part of the Green Line tunnel is a fully biodegradable polymer. Its slurry can be discharged to municipal waste water treatment plants. It can also degrade on its own (or with the addition of top soil) and be discharged into the storm sewer (21. 7). Bentonite, on the other hand, requires special disposal sites. Another advantage of polymer is that it can mix with fresh or salt water while bentonite requires fresh water.

Polymer has its disadvantages too. The initial cost of the material is several times higher than bentonite (though it promises to be repaid due to increased reuse factor and easier disposal, Table 1). Polymer slurry also does not form a filter cake. Polymer slurries prevent infiltration and stabilize ground through increased viscosity instead. Apparently, this mechanism does not work equally well in all
<table>
<thead>
<tr>
<th>ITEM</th>
<th>BENTONITE</th>
<th>POLYMER</th>
<th>COST_RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material concentration</td>
<td>60 kg/m³</td>
<td>3 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Material cost/Tonne</td>
<td>£120.00</td>
<td>£8000.00</td>
<td>1: 67</td>
</tr>
<tr>
<td>Initial Slurry Cost/m³</td>
<td>£7.20</td>
<td>£24.00</td>
<td>1: 3.3</td>
</tr>
<tr>
<td>Reusage Factor</td>
<td>2.5 times</td>
<td>8 times</td>
<td></td>
</tr>
<tr>
<td>Volume/job (m³)</td>
<td>4000</td>
<td>1250</td>
<td></td>
</tr>
<tr>
<td>Estimated Slurry cost/job</td>
<td>£28,800</td>
<td>£30,000</td>
<td>1: 0.96</td>
</tr>
<tr>
<td>Disposal @ £ 20.00/m³</td>
<td>£80,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disposal @ £ 5.00/m³</td>
<td></td>
<td>£10,000</td>
<td></td>
</tr>
<tr>
<td>Estimated Slurry cost/job</td>
<td>£108,000</td>
<td>£40,000</td>
<td>1: 0.37</td>
</tr>
<tr>
<td>Tonnage/job</td>
<td>240 Tonnes</td>
<td>3.75 Tonnes</td>
<td></td>
</tr>
<tr>
<td>Haulage</td>
<td>high</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Plant</td>
<td>high</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Mobilisation- demobilisation</td>
<td>high</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Labour</td>
<td>high</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Site Logistics</td>
<td>high</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Material Muck-Away</td>
<td>high</td>
<td>low</td>
<td></td>
</tr>
</tbody>
</table>

Source: Beresford. et al.
soil types. For instance, polymer slurry was tried at POS by ICOS for three 3 foot by 8 foot wells. In this soil, which had greater clay content, the polymer performed well (21. 6). But it may have presented some difficulties at NS (20. 13).

The use of polymer slurry at North Station is as follows: Millgard Corporation (a heavy foundation contractor) used a synthetic polymer to dig caissons at the site of the commuter rail platforms behind North Station. This was part of the first phase of the NSTIP. The platforms were raised to provide easier access to the trains (eliminating the need for steps). At the same time, thirty-five caissons were built to provide for future air-rights development. These caissons represent Millgard's first use of polymer slurry. They have subsequently used it on other projects including Phase II (the present phase) of NSTIP. Their use of polymer slurry in Phase II is in the interior caissons of the parking garage. The perimeter wall of the garage was constructed by ICOS Corporation of America, a contractor specializing in slurry walls, who used bentonite slurry for the perimeter. Now ICOS is proposing to use another polymer, different from the one used by Millgard, on the center wall panels of the Green Line tunnel extending out from the garage toward Nashua Street. This portion of the construction has not yet begun.
Concrete forming system.

In top/down construction, once the perimeter wall, interior columns or foundation elements and top deck are constructed, each level is "tunneled" out and a floor slab constructed. Of the four top/down projects in Boston up until now, two projects formed the floors as slab-on-grade and two used forms hung from the columns (Strickland forming system) (15. 15). North Station is the first to use a system in which the forms are supported from the top deck. The trade name of this system is Formeze. It is a patented, proprietary system which the contractor leases from Formeze. The advantage from the contractor's point of view is the relative simplicity of the system compared to Strickland. Formeze requires fewer holes in the top deck for equipment to let the forms down to successive levels (15.9). Formeze has another advantage on this particular job. The owner and the designer wanted to minimize the headroom needed to construct each floor because the soil conditions are such that the perimeter wall cannot be exposed very far (by excavation to each floor level) without support (13i.6, 20.11c). Formeze requires less headroom than Strickland because the forms are not as deep. While Formeze personnel do advise on the use of their product, the challenge of using it for the first time is the engineering that must be done by the contractor to insure proper reinforcing, etc. (20. 11c).
Super low ground pressure (SLGP) equipment.

In the Post Office Square project there was concern about the ability of the soil to support standard earthmoving equipment. On that job the contractor, J.F. White, purchased "super low ground pressure" - SLGP - equipment from Caterpillar. The same type of equipment is being used on the North Station project by its contractor, Modern Continental. This is the second use of this equipment for construction in the Boston area and Modern Continental's first use. The equipment exerts a 5 psi load on the soil (compared with about 8 psi for conventional equipment) (15. 4). It is made by Caterpillar, an American firm, with Mitsubishi Heavy Industries, a Japanese firm. This model, CAT 953, is made only in Japan. One contractor said the equipment was originally developed for use in soft, wet earth (like rice paddies) in Asian countries (15. 4).

In this research there will not be much emphasis on this equipment. Its use is most interesting for the relationship between the two contractors who have recently had need for it, J.F. White and Modern Continental, and for the role of the manufacturer in provision of this new technology.
Precast sequential construction.

The primary technology of interest on the Jamestown Verrazano Bridge (JVB) is the method of constructing portions of the bridge by precasting concrete segments and lifting them into place. While such a method is not in itself new, the size of the segments and the fact that they are being lifted over water has posed several technological challenges to the contractors. These include: how to fabricate the segments in a controlled environment (i.e., not on site); how to transport them to the site (their size and weight make them unwieldy and their post-tensioning makes them sensitive, in a sense more brittle); and how to lift them into place from a barge in tidal water without cranes strong enough.

The segments in question are full cross-sections of the bridge and span almost the entire distance between piers. Each is 167 feet long and weighs 2400 tons, possibly "the heaviest concrete segmental units ever lifted in the United States" (RIDOT). Fifteen such span segments are to be precast in a casting shed built especially for this project in Davisville, R.I. Each unit is cast in six concrete placements as it slides through the 300 foot long casting facility on 24-inch deep steel beams. These beams are supported on steel piles driven to rock and topped with stainless steel plates to reduce friction. These plates are covered with dishwashing liquid to lubricate them in a manner
less offensive to environmental concerns than conventional lubricants.

Before transport to the bridge site each span segment is transversely and longitudinally post-tensioned by means of steel post-tensioning tendons. Temporary compressing rods are also added to strengthen the segment for its sea journey, and concrete diaphragm walls are cast to provide support for the lifting wells through which lifting strands will run when the segment is being placed. When all this is completed the unit is jacked to two rails positioned over the water. At low tide a barge comes in under the segment and using the rising tide and ballast tanks picks up the segment and begins a two-hour trip to the bridge.

Once the segment has arrived at the bridge it must be anchored in position between two piers and rigged for lifting. No crane will lift such a weight into place so six lifting beams using six 1000-ton hydraulic jacks, three on either pier, will slowly lift the segment into place. On either side of the span segment two-foot closure spaces are left to be formed and filled with concrete to complete the span. (The above description is condensed from the Jamestown Verrazano Bridge Newsletter, Fall 1990, RIDOT.)
Results of North Station and Jamestown Verrazano Bridge case studies

While the interviews were conducted in a largely open fashion in which interviewees could comment on any aspects of the projects they thought interesting or innovative, there was an attempt to solicit information that would shed light on the patterns found in the POS case study. In analyzing the data from the North Station and Jamestown Bridge projects they were first divided into the categories derived from the POS study. Thus points of reinforcement or contradiction could come out more clearly. Some data did not fit neatly into the previously defined categories but seem to add new insights into technological development in construction. In this section of the thesis the data will be presented according to their relationship to the POS results, following the same order of categories.

Communication

Communication in the industry in general. In these sets of interviews there were comments about some of the same sorts of things that came up in the POS interviews: that technologies take a long time to come to the U.S. from Europe (21.10) and that the separation of design and construction can cause difficulties (22.5b, 20.12, 14d). But there were three areas that were dwelt on most: exchange of knowledge
among members of the industry, vehicles of communication of knowledge about technology, the nonproprietary nature of technological developments in construction.

Interviewees were asked how easily they can visit sites of other contractors or get information about technologies from other engineers. While one designer from POS indicated that know-how is traded freely, interviewees from NS and JVB indicated that there are conditions and limits to this flow of information. One stated that information and site visits are usually the result of personal relationships because there is rivalry between firms within one’s specialty (20.17). Another (a contractor) admitted that he had visited a site where a competitor was building a structure similar to one he was to build but suggested that this visit was “unofficial” and arranged through a friend connected to the competitor’s firm. At the same time, another contractor indicated that he usually can get access to the sites of other contractors, and if not, he goes anyway (22.21). This same contractor indicated that a certain amount of “trading” of information comes from firms working together on projects (in a joint venture, as general and subcontractor, as contractor and construction manager) and from people moving around within the industry and bringing technical approaches they saw developed in firms they previously worked for (22.21, 20.17). But he also made clear that there are limits. Even if two firms work together on a project,
neither will allow its own cost information to get out (22.21). Another contractor who said visiting sites is common also indicated that much of the information one gets about others' projects comes after you bid on your own so it does not help you get the job; it helps you do the job (23.9).

Another avenue for trading information about construction developments was brought up by an interviewee. In the area of rail transportation, technological information regarding construction is traded between competing railroads. Though they compete within certain corridors they also support each other since they feed traffic to one another (14.17). It would be interesting to know if other "extra-industry" trading of knowledge about construction technologies goes on.

When asked how they keep up to date with technological developments, engineers gave similar answers to those on the POS project: professional magazines, technical journals and conferences, manufacturers, suppliers, colleagues (18.2; 23.9; 14.7,10; 21.10). In these interviews two individuals explicitly cited European sources (literature and personal contacts) (21.10, 14.10); one even stated that American technical literature is not so good (presumably in his field) (14.16). Another source of technological information also arose in these interviews and that is the Federal government,
specifically through transportation programs like the Urban Mass Transportation Act (UMTA) (14.7) and related government sponsored meetings that provided an opportunity to meet others with similar concerns (14.13). The same interviewee mentioned the Transportation Testing Center in Pueblo, Colorado as a center originally funded by the government and now supported by companies in the transportation industry (14.18). He also mentioned a transportation center in Cambridge as a good source of knowledge about transportation technologies (14.7).

Yet another source of technical knowledge is the consultant or expert who may be hired by designer, contractor or owner. They have worked on different projects perhaps even around the world. One engineer recalled having an expert who was also a consultant on the English Channel tunnel (20.16).

Three individuals discussed the non-proprietary nature of construction technologies. One stated that the first time someone does something new, the entire industry knows about it. That is why, he says, construction companies will not invest in the development of new technologies: the results of their investment will be freely available to everyone else (22.17). This same contractor said that he is sometimes wary about speaking to Engineering News Record because that magazine is one of the ways that others know what he is doing
(22.19). At the same time another contractor lauded ENR for the same reason (23.9). An engineer with the MBTA gave an example of how that organization spreads knowledge about construction technologies. They build many similar facilities but with different contractors. If they see that one contractor does something in an effective and cost-efficient manner they will not hesitate to pass on the method to other contractors working for them (14.19).

Two engineers commented on the use of patents to protect new technologies in construction. One said he had seen a contractor pay a royalty on a technology only once in his more than 40 years of experience (22.18). Another mentioned a patented component in a system he is using and thought the patent was useless because anyone using the component in the field could figure it out and make small changes to it (15.14). That technology seems actually to be protected by entry barriers as will be discussed later under the role of the specialty contractor.

**Communication within firms.** One contractor mentioned that a firm he used to work for had a system where new ideas were written up and, along with drawings, became part of a "field handbook" from which others in the firm could learn of these ideas and apply them. At his present company no such formal system exists (23.8). At his present firm, and at the firm of another contractor interviewed, new ideas are carried
from project to project by the movement of people. In some cases there are people who habitually work on certain kinds of projects (like bridges). To the extent that this is the case, a certain amount of transfer of technology to appropriate projects is reasonably achieved (15.24).

A designer brought up another mechanism through which technological knowledge is diffused through his firm. This mechanism is the peer review that is performed in-house on each design (20.16). This approach does serve to bring individuals specifically experienced in similar projects into each new project for the purpose of checking, critiquing and making recommendations. If these individuals have developed or observed any new methods this peer review would provide an opportune moment to let them be known: the design is not fully determined yet it is substantially done so that the significance of any new idea will be immediately understood. (The only drawback would be that new ideas which only make small improvements may not be able to be adopted economically.)

Visual presentation of information. Another instance of the importance of visual presentation of information arose in the North Station project. A complex array of structural steel was to be assembled for the top deck of the parking garage. From the design drawings it was not clear how the array of steel was to be erected. The reason given for this
was that the configuration of the steel could not be visualized from the drawings and therefore an exact erection procedure could not be determined. To solve this problem the contractor's staff created an isometric drawing of the steel from the design drawings. Then it became clear which pieces must be placed first so that others will not be obstructed (13ii.1, 15.29). One visual presentation (plans) was sufficient to specify products, but a different visual presentation (isometrics) was required to determine process.

Experience. Most interviewees indicated directly or indirectly that their firms' experience was relevant to their being on the particular project being studied. The contractor on JVB had done several similar bridges (23.1). The construction manager on JVB stated that his firm got the job because of their bridge experience (22.9d). One of the subcontractors on NS is very experienced — they have been involved with every top/down project in Boston, except the first one, as well as many other projects involving slurry wall construction (21.3). Apparently they developed the slurry wall method using bentonite (21.1). The other foundation subcontractor at NS also was involved with several Boston area projects including two top/down projects (16.1) though the platform raising project at NS, immediately prior to the parking garage construction, was their first use of polymer slurry (16.5). The designer on NS had also been involved with three previous top/down projects in Boston.
(20.2). Nevertheless, the interviewee indicated that their experience with the latest of these jobs, POS — on which they had the most intense involvement — was not relevant to their getting the NS job because they had been chosen for NS in 1983 (20.8), four years before the firm was involved with POS (5.1).

Once again the question arose of whether or not it was helpful to have knowledge of the type of job or job site in order to get a new job. Once again the answer is ambivalent. Sometimes what you do not know helps you because you will have an open mind without preconceived notions, according to one contractor (15.12). On the other hand the same contractor thought his previous work on the commuter rail platforms at North Station did give him knowledge of the site (the soil and obstructions in it) which may have helped him get the parking garage work (15.13).

The issue of the role of joint venture partners will be addressed later under Role of Participants. Of the four joint ventures involved in these two projects only one seemed to contribute experience systematically to the job (management of the job was undertaken by both partners). One other partner clearly was known for experience in the kind of construction under way but it is not apparent that this experience is a regular contribution to the job (15.10). The
other two joint ventures were stated to be primarily financial partnerships (22.10, 21.11).

One engineer on NS stated that experience from previous projects causes one to learn a wide variety of things, from specific requirements made on the contractor to general things to look out for (20.1). Another engineer on the project thought that the firm certainly utilized things they had learned on POS for NS (19.3). Even though he himself did not have experience with slurry walls, his previous experience with caisson construction (including on the commuter rail platform job) was very relevant to the current project. For instance, both used polymer slurry for digging the caissons (19.4).

Experience is very much embodied in the individual person. An older engineer with more than 40 years of experience said that a lot of what you learn goes with you when you die, though you try to pass on as much as you can. While he agrees that there should be some kind of program for passing on this kind of information, he does not think expert systems will work well beyond very specific problems with a "go-no" (binary decision tree) structure (22.20). An example of how important experience can be is one engineer who, though formally trained in architecture (bachelor's from Cornell, master's from MIT), has worked for almost four decades in the transit field making him a broad-based expert
at the MBTA (14.9). Although much of his knowledge is encoded in papers, drawings and even embodied in completed projects, most of it is in him.

**Role of the project**

**Project as classroom.** In the above section on communication in the industry the role of projects as a vehicle for knowledge about new technologies and how they work is suggested by the importance of site visits to other projects and articles about projects in *Engineering News Record*. But the project one is actually working on also provides opportunities to learn more about technologies. Interviewees from both projects gave examples of how they learned the limitations and proper implementation of technologies because of the demands made on these technologies in the context of particular projects.

On North Station (and previous similar projects) the designer learned that controlling the maximum depth of the excavation in stages is crucial and so they posed appropriate indications and precautions to the contractor. They also learned that the ground floor must be "locked in" early. This was also pointed out to the contractor (20.10). Apparently, precautions to the contractor are particularly necessary in these areas because he will tend to want to dig deeper and with more of the top deck open since this makes
his job faster and easier. The same designer learned which kinds of drilling procedures and types of foundation elements are appropriate in different soil conditions through involvement in four top/down projects in Boston (20.14).

On the Jamestown Bridge project the post-tensioning and lifting contractor, though highly experienced in both areas, learned more about his own technologies as a result of the challenges posed by JVB. In particular the contractor was surprised to find a fatigue problem with the strands in the post-tensioning cables. These cables are only loaded to 40% of their ultimate strength, as a safety factor. But after these 80 foot cables were suspended in high winds for two or three weeks they found fatigue failure at the point of anchorage. This caused the contractor to modify the lifting technique to better control the angle change in the system (24.4).

**Project as laboratory.** As in the POS project, NS and JVB have also provided occasions for incremental improvement of construction technologies. The modification of the lifting apparatus at JVB is an example of this. When asked if improvements and small developments take place on projects the answer is always an enthusiastic yes (21.12, 15.21, 23.7, 13ii.2). For example, on the NS platform raising project the method of raising the platforms was improved with each platform till they "had it down to a science" (15.27) and the
contractor had to develop a way to build a road which would cross the tracks and be easily adjusted as the platforms were raised (15.28). Several details were developed in the design, casting, transporting and lifting of the precast segments of JVB (JVB-SV.3, 22.12). Sometimes the improvements almost sound silly: dishwashing liquid as an environmentally sound lubricant (JVB-SV.3), or using a basketball to obtain a continuous column of concrete in the filling of the slurry wall (the ball is pushed through the pipe by the concrete to the bottom of the excavation and then floats to the top of the slurry (13ii.3).

Improvements were directly linked by interviewees to the specific requirements of the job at hand. One contractor said that there are not empirical formulas to handle everything so problems are often solved on a trial and error basis. There is always enough difference he said, from one job to another to require at least one change. Some examples of development or acquisition of new technologies due to the specific demands of the projects are as follows: The use of Formeze forms on NS led the contractor to use a new stud rail developed in Canada to avoid punching shear in the top deck from which the forms would hang (15.21). Recall that the use of Formeze and SLGP earthmoving equipment were also imposed by specific site conditions (13i.6,7). The close tolerances on JVB required that the precast segments be strengthened: the segments originally could take a movement of 1/8 - 1/4
inch, which was less than the rolling tolerances of the beams on which the segments rested (22.16). The need to take into account the tides in Narragansett Bay led the contractor on JVB to develop very careful coordination schemes for tug boats, barges and lifting (23.2,3). The construction manager on JVB also indicated that part of the new procedures and redesign were required because the designers of the precast segments designed them for performance in place, not for the process of construction (including transporting and lifting) (22.13). The effects of these processes are often project specific (particular weather, sea, soil conditions, etc.) Another example comes from a specialty contractor who had to have a special auger made with the pitch of the auger flight decreased so that soil wetted with the new polymer slurry would not slide off when the auger is drawn from the ground (16.7). (Other references to the project-orientedness of technology in construction include (20.11, 21.4, 6, 13).)

While unique project situations do give rise to incremental improvements in technology, engineers also realize that this same reason leads to a lack of continuity in the developments. One contractor said he thought there must be a certain "loss of technology" because it is developed in response to the unique requirements of the present job, requirements which one may not see again (15.25). Another engineer said there are plenty of small improvements but "When will you ever use it again? They're
unique to the project." But then he added "But you draw on it, just like in education." (13ii.2).

In addition to small improvements one specialty contractor spoke of a project his firm was involved with about 13 years ago which led them to develop a whole new system and equipment. (The project was a severely leaking dam.) (21.12)

Just as in the POS case study the later studies uncovered a certain element of testing or experimenting taking place on projects. The slurry wall contractor is testing a polymer slurry they have never used before on a small portion of the Green Line tunnel at NS. This way they can compare its behavior to bentonite used on the same site and they can try it on a small, safe portion (15.8; 21.5,7). This contractor stated that while they do not do any laboratory testing of new materials or products, they will conduct these tests on projects if a new product is around and the circumstances (space, time, soil conditions, owner) of the project permit it (21.8). Another foundation contractor tested a polymer slurry on a caisson for the Central Artery before using it at NS (15.2). A consultant for the designer said that they had tested some ballast mats on earlier Red Line work for the MBTA, taking before and after readings to judge noise and vibration isolation (18.8). The MBTA as an "owner" will sometimes try out new
technologies on portions of rail under construction (14.4, 5, 11d). While the MBTA is not "in a hurry to be first", as one engineer there stated, they will do some things that are experimental, or even be the first in the U.S. (14.3).

As on the POS project, the geotechnical engineers on NS took a highly observational approach, monitoring many aspects of the work, collecting data on soil movement, ground water levels and progress on construction. One engineer indicated that this not only provided data for monitoring the current project and to study for future application, but it also provides data to defend oneself against claims on the project. He said there were no major claims on the POS project which was unusual for such a job (20.5).

Importance of process

The importance of process in construction and its relationship to the development of technology in a project context was apparent in three issues brought up by respondents. First, the contractor on NS chose the Formeze forming system because of the simplicity of its process (15.2). Second, the contractor had isometric drawings made of the steel array of the top deck precisely to determine the process of erection (13ii.1, 15.29). Third, on the JVB project modifications and redesign were required to
accommodate the process requirements imposed on the contractor by the natural conditions of the site and the loads that would be imposed on the precast bridge segments in the process of casting, transporting and lifting them. (22.13,16; 23.2,3).

**Role of participants in project**

In this section some of the same participants' roles will be discussed as were discussed in the POS study. In addition some new roles came out in the NS and JVB projects. These are: public owner, specialty contractors, joint venture partners and manufacturers.

The major participants in the North Station project are:

**Owner:** Massachusetts Bay Transportation Authority

**Designers:** Parsons Brinckerhoff/Seelye Stevenson, Joint Venture

**General contractor:** Modern Continental/Ohbayashi, Joint Venture
Foundation subcontractors:

ICOS Corporation of America/Nishimatsu Construction Company, Joint Venture (perimeter wall and Green Line tunnel

The Millgard Corporation (interior caissons for garage)

The major participants in the Jamestown Verrazano Bridge project are:

Owner: Rhode Island Department of Transportation

Construction manager: Perini Corporation

General contractor: Atkinson/Kiewit, Joint Venture

Post-tensioning and lifting contractor: VSL

Owner. As mentioned earlier, the MBTA, as the "owner" of the NS project acts as a means of spreading knowledge about technologies and new methods among members of the construction industry (14.2). One example given related to the development of a track installation technique which the MBTA passed on to other contractors on subsequent jobs (14.19) and in fact published an account of in a presentation for a rapid transit conference (Williams 1984). While "not
in a hurry to be first" (14.3), the MBTA is active in determining better ways to construct and run its system (Williams 1983, 1984). One individual in particular plays an outstanding role in the gathering and diffusion of knowledge about all kinds of technologies related to the MBTA's responsibilities. He is a major source of "cross-fertilization" in the organization (14.12). This individual has much personal motivation to study new technologies, even to the point of making trips to Europe for this purpose largely at his own expense (14.7,11d,20). Apparently, the MBTA also has a lab for testing materials (20.15) and has actively worked to have codes and testing procedures changed to accommodate new components into their system (14.4). The role of the railroads, as owners, in the spread of knowledge regarding construction technologies was also mentioned earlier (14.17).

**Designer.** The designer in the NS project did not seem to be highly instrumental in the introduction of new technologies. In fact, they seemed to be more conservative in their specifications while the contractors proposed newer approaches (20.10,11c,12). In the JVB project the original design for a fully cast-in-place bridge was modified because of the contractor's proposal to construct some sections as precast segments. The redesign was done by the subcontractor who specializes in post-tensioning and heavy lifting so this will be discussed under the role of specialty subcontractors.
Contractor. Contractors exhibited a much more active role in the introduction of new technologies in the NS and JVB projects. At North Station the general contractor proposed the use of the Formeze forming system though the designers advised against it (20.11c). They also bid to use a polymer slurry for the interior caissons though the designers had considered ruling it out. Instead they made it clear that the contractor would need permission to substitute for bentonite and would receive no extra money (20.12). The designer also claims that the contractor did have problems with both technologies. Apparently the contractors chose them for the cost reduction they expected would result (from a simpler forming system and a slurry which was easier to clean and reuse). On the JVB the contractor proposed the use of precast segments while the original design had been cast-in-place (22.4). As already discussed this method did entail the clearing of several technological hurdles. (It should also be noted that this modification was proposed by the first contractor who soon lost the job. It was then included as an alternate when the job went out to bid again and a combination of cast-in-place and precast segmental methods was chosen by the new contractor (22.9f).)

Another role of the contractor also became clearer in these two projects. That is the responsibility of the contractor to "engineer" the details of the process by which
he will achieve the final constructed facility. While the bid documents may pose certain requirements or limitations there is still much which the contractor must do. His role is the design of the process of construction. One example is the road system the contractor had to develop for the NS platform project which had to avoid damaging the tracks with heavy vehicles and which had to serve at three different levels as the platforms were raised (15.28). The same contractor had to redesign the reinforcing for the floor slabs of the parking garage to take the temporary loads imposed by use of the new forming system (20.11c). One designer indicated that he does little to specify materials; materials technology is “something the contractor must develop” (19.5).

On the JVB project the contractor also had to design the entire process by which the precast segments would be fabricated, transported and installed. They do have as a subcontractor the firm that designed the post-tensioning but the contractor claims that this firm did not totally design the system. The general contractor’s engineering group worked out the details and made modifications so that the system would work (23.5). This is a corroboration of the JVB construction manager’s comment that the designers design something for where it will “end up”, not for how it will get there, thus leaving the contractor to work out the process details (22.13). The overall development of the process of
implementation for construction is done by the contractor's engineering and estimation groups, according to one contractor (23.6). Sometimes a company will have a "construction support group" specifically.

Geotechnical engineer. Since NS is an underground job, geotechnical engineers were involved with it in much the same way as POS. Their role is basically the same in both projects, involving both design and monitoring, only noting the apparent increased conservatism exhibited with respect to technologies at NS.

Consultants/advisors. The consultant interviewed for NS is an acoustical consultant whom the designer engaged to study the vibration and noise that would be transferred to the structure from the moving trains. Since the technologies with which they are concerned (acoustical track fasteners) are not yet in use on the project and since they are not so much a construction technology as a rail technology, I have not concentrated on them. Suffice it to say that as consultants they took measurements of the vibrations produced by moving rains and studied the possible ways of isolating these vibrations (13i.8; 14.8; 18.1,7).

On the Jamestown Bridge project the subcontractor who designed the post-tensioning is also the lifting contractor.
Part of this role involves providing advice and equipment for heavy lifting (22.11, 24.1b).

**Specialty contractors.** Specialty contractors played a large role in the introduction of new technologies in both the North Station and the Jamestown Verrazano Bridge projects. On both projects specialty contractors convinced the general contractor to bid the job using their particular technology.

On NS Millgard Corporation, a heavy foundation contractor, convinced the general contractor to go with a polymer slurry on the interior caissons of the parking garage (13i.2; 16.3,6). ICOS, specializing in slurry walls (developers of the bentonite system) did the perimeter walls of the garage with bentonite. They also will do the Green Line tunnel portion of the project and have proposed the use of a different polymer in part of this tunnel (21.1,5,7). Both of these specialty contractors also develop special tools and equipment. ICOS develops much of its equipment in Italy (21.9). Millgard develops about 75% of their tools for environmental (hazardous waste) work in-house and probably 50% of their foundation tools (16.9).

On JVB, VSL, a contractor specializing in post-tensioning, was responsible for the proposal to precast portions of the bridge and lift them into place with post-
tensioning tendons. They proposed this plan to the contractors who were to bid on the job and several contractors included the scheme in their bid. Once the job was awarded VSL redesigned the bridge for post-tensioning and provided the form travelers used to cast the cast-in-place portions of the main span (24.1a). VSL is a wholly-owned licensee of VSL International in Switzerland where all of their R&D goes on. Their specialty in post-tensioning has led them to other areas — retained earth, heavy moving and lifting — which are applications of their basic technology (24.3). This led to their second role on JVB, that of lifting contractor, in which they provide the post-tensioning equipment, jacks and lifting beams, engineer the lifting system including hydraulics, structural and construction engineering, and provide on-site advice regarding the lifting procedure (22.11, 24.1b).

Manufacturers. Just as the specialty contractors were sources of new technology, a manufacturer on NS — Formeze — is the source of the new forming system and an on-site consultant when the forms are in use. While they do have a patent on their system, the real protection seems to come from the large investment necessary to enter into competition with Formeze. The company has invested in equipment and in hundreds of forms already made (15.14).
Caterpillar, the manufacturer of the super low ground pressure earthmoving equipment, CAT 953, offers a "guaranteed buy-back" as an incentive for a contractor to purchase their equipment. Caterpillar guarantees they will buy back the equipment from the contractor after the job. Cat can then sell it again, retrofit it to standard U.S. tread or export it. Such an arrangement is apparently not unusual (15.17). On the other hand, the contractor can opt to keep it. The contractor on NS does not think he will do this though it would give him the same advantage J.F. White has if he kept his equipment (15.18). (It is interesting to note that despite the statement by a project engineer at J.F. White that they would probably rent their equipment to other contractors (2.16), J.F. White refused to rent their SLGP dozers to Modern Continental once MC had the NS job (15.5).)

Joint venture partners. Between North Station and the Jamestown Bridge members of four joint venture partnerships were interviewed. Three clearly stated that their joint venture partners were primarily or purely financial partners. Nishimatsu provides working capital for ICOS but no specific technical expertise (21.11). Kiewit is a financial partner for Atkinson though they do sometimes provide advice or personnel (22.10, 23.10). Ohbayasi is primarily a financial partner for Modern Continental though they are experts in slurry wall construction. Apparently they have built the deepest slurry wall in the world (15.6). Their expertise
becomes helpful in areas like scheduling and assessing the work of subcontractors (15.10)

Only the Parsons Brinckerhoff/Seelye Stevenson (PBSS) joint venture appears to involve appreciable amounts of technical and managerial expertise from both partners. The project manager is from Parsons Brinckerhoff and the project engineer is from Seelye Stevenson (19.2). Both firms have structural and civil capabilities; both have transportation expertise. Parsons has heavy construction and geotechnical expertise. Seelye Stevenson has electrical and mechanical capabilities and experience in railroads (19.1, 20.18).

Industry and firm issues

This category is somewhat miscellaneous but certain data do fall into the categories previously outlined for the POS project.

Sources of construction innovations. In addition to citing Europe as a source of construction innovations (17.2; 21.10; 14.1,5), the oil industry was also mentioned. Polymer slurry technology came from the oil industry which uses a variety of slurries and techniques depending on the soil conditions or formations encountered when drilling for oil. Apparently these polymer slurries have only been commercially available to local contractors for about five years. One
foundation contractor thought the North Station commuter rail platform job may have been the largest foundation application of polymer slurry yet (16.8).

**Separation of design and construction.** The separation of design and construction seems to pose several difficulties in the adoption and implementation of new technologies, though the difficulties do not seem to have been insuperable on either project studied. Designers are extra careful in specifying things since the contractor's plan will not be worked out with the designer (19.5; 20.12,14d). When the contractor proposes a different approach it may require a redesign which means time and money (22.4). Sometimes more data is gathered after the job is awarded and requires a change of construction and design (22.5b). As mentioned earlier, designers do not always take into account construction requirements and processes ⇒ more design — some of which may have been avoided — is done by the contractor's engineering staff (22.13, 15.29, 23.5).

**Private vs public ownership.** The issue of private vs public ownership arose in the context of the separation of design and construction in the bidding process (19.5, 20.14d). It also arose in the rigorous design process one engineer observed on POS and which he attributed to the mixture of public and private concerns and the desire of the
consortium of private owners to explore every alternative (20.3).

**Testing standards and codes.** Although I decided not to explicitly cover the track fastener technologies used by the MBTA, an interesting history is attached to them which is worth mentioning. It pertains to the persistence on the part of individuals at the MBTA in finding a way for fasteners designed in Germany to pass inspection for use in the U.S. The fastener in question was the soft “Kölner egg”, a fastener which works mostly in shear to absorb vibration from a moving train. The tests in the U.S. were designed for stiff fasteners which work in compression. Getting the fastener to be approved required: modifying a test to account for the use of a spring fastener rather than a bolted down fastener (for which the test was developed); convincing the testing authorities that the decreased electrical isolation — due to the carbon black in the rubber “egg” — would not cause problems with lightening since the fasteners were used in subway tunnels; and discovering that the cyclic load test was copied from other tests requiring loads much greater than a subway rail would ever experience. In fact, an engineer at the MBTA said if the egg had been modified to pass the tests it would not have been an effective vibration isolator. But to get it approved required dogged tenacity (14.4).
(The university/industry relationship was not explored in these case studies.)

**Analysis of results**

In general the results of the North Station and Jamestown Verrazano Bridge case studies reinforce the results of the Post Office Square case study. Again, fragmentation of knowledge about technologies is found accompanied by its availability. What has come out more clearly in the latter two case studies is the wide variety of mechanisms through which knowledge about construction technologies is spread through the industry. Also, the importance of the construction project as classroom and laboratory is reinforced at NS and JVB with a picture of a more active role for the contractor beginning to show itself, particularly in the area of developing construction processes.

First, looking at the communication or availability of knowledge about construction technologies, we find mechanisms of diffusion which did not arise, or not so clearly, in the POS interviews. One mechanism involves different contractors working on the same job, as joint venture partners, as construction manager and general contractor (as at JVB) or as contractor and subcontractor. Another is the general movement of individuals throughout the industry. Government
sponsored programs were cited as good vehicles of communication at least in the area of transportation-related technologies. The owner, as an employer of several different contractors for similar types of work, is also a diffuser of newly developed techniques. At least one instance of a "gatekeeper", an individual highly motivated to gather knowledge about technologies, was found in the case studies. Peer review of design work may also be a vehicle for passing on experience and knowledge about technologies.

One issue that was systematically pursued with contractors and designers in the NS and JVB case studies was the frequency and efficacy of trading of knowledge with competing colleagues. While some of the answers to questions in this area are the mechanisms mentioned in the previous paragraph, some comments also related directly to a phenomenon known as "know-how trading" (von Hippel 1988). Specifically this trading is often in the form of visits to project sites. Many interviewees stated that such visits occurred or were even common. Nevertheless, a couple of limiting factors were expressed by some respondents. Two indicated that such "trading" occurred if one had a personal, friendly relationship with someone in the rival firm. Another indicated that the information one could get or the visit one could make was often after the bids were in or even awarded on a new job. Thus such information does not help one get the new job but can help one successfully and
profitably do the job. An economic explanation for this behavior is explored in Chapter VII.

In the area of the role of the project as the context in which construction personnel learn about and develop technologies, many data reinforced the conclusions drawn from the POS study. Members of the construction industry, as explained in the section relating the results of the case study, depend on projects to learn about technologies and specifically to learn if and how they work. The incremental (and sometimes not so incremental) development of technology often stems from the demands of the project at hand. But the role of the contractor came out more strongly in the NS and JVB as being a more active one. First, on both projects it was the contractors, not the designers, who pushed to use more innovative methods or materials. Second, the role of the contractor in the development of process technology (construction methods) became much clearer. This reinforces the statement of a POS engineer that the role of the contractor is to handle the execution of the construction (3.4). Especially when he is proposing to use a new technology, a contractor may have to spend a substantial amount of effort in engineering the construction process so that the innovation will work and he will still make a profit.
The role of specialty contractors should not be overlooked in assessing the role of the general contractor in proposing the use of a new technology. In both projects it was specialty contractors (foundation, slurry wall and post-tensioning specialists) who "sold" the innovative method or product to the contractor so that he would include it in his bid. The specialty contractors seem to be akin to manufacturers in that they are usually selling a particular product or process, but they also do the actual work. They, in turn, can be vehicles through which manufacturers get their products (polymer, for instance) into the construction industry, rather than through general contractors. They may also develop their own technologies as in the case of the specialty contractors interviewed who developed much of their own equipment. General contractors, on the other hand, have no incentive to develop materials or equipment. They leave this risk up to specialty contractors and suppliers who set up arrangements that keep the investment risk low for the contractor. Contractors can lease equipment (like the Formeze forms) or even buy it and sell it back (like the CAT 953 equipment).
Chapter VII

THE ROLE OF CONTEXTUAL KNOWLEDGE
IN CONSTRUCTION

Introduction

The results of the case studies discussed in the previous chapters can be unified through the concept of contextual knowledge. This chapter presents a conceptual framework of the way contextual knowledge operates in construction to influence behavior in the industry in the areas of education about and acquisition and development of technology.

Description of conceptual framework

Recall from Chapter II the difference between formal and contextual knowledge. Formal knowledge involves the abstraction of elements of relationships from specific
occurrences to form general or "universal" ideas. Once this is done, the specific context in which the elements and relationships were experienced is no longer necessary and the formalized knowledge can be transmitted via means of communication which are also independent of the specific context, i.e., formal means of communication: books, papers, lectures, diagrams. These means (as is this knowledge) are not only independent of context but of the person or persons who initially experienced the specific occurrences which gave rise to the formalized knowledge.

Contextual knowledge, on the other hand, is that immediate knowledge of the occurrence in its specific context. It involves the immediate synthesis or drawing together, of the parts as they exist in relation to each other in their actual circumstances so they can be seen as an organic whole. This process is accomplished by the knowing person who integrates knowledge of diverse things into a unity due to the unity of the knowing subject. It implies a sort of openness or receptiveness to the whole as particular experience of reality rather than the probing analysis required for the production of formal knowledge. Formal means of communication do not preserve this organic unity. Rather, the person possessing this knowledge of specific occurrences in their particular contexts, i.e., the experienced person, is a better vehicle of contextual knowledge.
Figure 4 depicts a schematic diagram of how this contextual knowledge can be said to operate in construction. Construction, as an activity, is a process that is not well formalized according to the description of formalization given above. The process as a whole is not governed by a set of physical or chemical laws as processes in the nuclear, chemical, materials and electronics industries are. Its products tend to be unique and complex and the environments in which these products are produced are also diverse, complex and relatively unpredictable. All of this leaves the construction process with very little in the way of a formal conceptual framework for understanding and analyzing its workings.

**Project-orientedness of construction**

Because of the lack of formalization of the construction process, knowledge about construction is not formalized and therefore not communicated through formal means. Rather, since the knowledge is one of specific occurrences (remember specifics do not occur in the abstract but in particular circumstances or contexts) it is a knowledge of things in their particular contexts. Knowledge of this sort, since it is not independent of context, cannot be learned or transmitted independent of context. This means that context
Figure 4

Given a process which is not well formalized

Knowledge of that process will be largely context dependent:
- knowledge of the functioning of the whole
- not able to be transmitted by formal means

Knowledge is fragmented and must be transmitted in context by a vehicle capable of so doing: the experienced person

Construction is a largely nonformalized process; it is not related to a scientific discipline or set of physical or chemical laws

The process is largely understood through specific contexts. In construction these contexts are projects.

This general "project-orientatedness" of construction is exhibited in various types of knowledge-related behavior:
- learning about construction process through the project
- learning about technologies through the project
- improving/developing technologies through the project

all of which are brought about by experienced personnel

Conceptual Framework: the Role of Contextual Knowledge in Construction
becomes the locus for transmission of knowledge. In construction that context is the project.

**Fragmentation of knowledge in construction.**

The project-orientedness of construction produces a fragmentation of knowledge in the industry: knowledge about construction technology is possessed by many individuals and groups situated in various specific contexts but is not well communicated among them. Since this knowledge must be gained through direct personal experience, fragmentation of knowledge comes about in construction in two ways. First, the direct acquisition of contextual knowledge requires spending time gaining experience. This leads to a certain specialization since each person must be immersed in his particular “contexts” to gain enough knowledge to function well — vertical fragmentation of knowledge among disciplines and subdisciplines. Second, the need to gain knowledge through direct experience, often through trial and error, means that many people are facing similar problems on different projects and cannot easily learn from each other beforehand through more formal communication. So there are often many people facing similar problems simultaneously or even years apart and having to solve them from scratch because of the lack of formal communication of lessons learned and because one often has to be in the middle of the problem before one recognizes that it is similar to other
problems and by then it may be too late to effectively take advantage of existing solutions.

In turn, this fragmentation of knowledge affects the behavior of the industry in areas pertaining to the transfer or development of knowledge, such as education and acquisition and development of technology.

Learning about the construction process itself: project as classroom. A large part of learning takes place "in context" in construction, that is, on the project. This is true of apprenticeships in crafts and of superintendents who move up from the trades. But it is also true of those who are formally educated in engineering or construction management who must learn the realities of their job from experience. Even designers whose work is less affected by the complexities and unpredictability of the construction site place a high premium on field experience. This was the case with the geotechnical engineers interviewed. Often the consultants used on a job are valuable for their practical experience (although many consultants are also called for their formal or theoretical knowledge — both types were present on the POS project.)

Engineering judgment. From comments made by several interviewees it seems that the specific knowledge that is developed through context or experience, the knowledge
learned in the "project-classroom," is what is usually called engineering judgment. It is that ability to know what to do in circumstances that are not clearly explained, predicted or solved by whatever formalized body of knowledge exists. It is the knowledge that determines specific actions - the execution of the ideas. It is practical judgment which must be and can only be exercised in specific circumstances even when it is derived from more general knowledge.

Although engineering or practical judgment is only exercised in specific, actual situations, it is linked to previous knowledge. But even this knowledge has been gained in other specific situations. It is a knowledge gained inductively from one actual experience after another and then applied to new situations without much of a formal explanation for why it might work. More formalized knowledge can be developed from this process, but in itself the process differs from the deductive process of applying general principles to specific circumstances. Even this latter process requires an element of practical judgment whenever the actual circumstances present something not covered by the general principles or which the general principles only deal with using some degree of probability: this "usually" works. Practical engineering judgment is the decision that this circumstance is or is not one of those that fall under the "usually." It is the decision of
specifically what to do now to make something work. Unlike the application of formal knowledge wherein the reason for its application is that the "form" or theory indicates its applicability a priori, the reason behind an act of practical judgment is that experience shows that it works.

Therefore, the development of practical judgment necessarily occurs through experience, through practice. This would explain why so many individuals interviewed put such emphasis on the integration of practical experience with engineering education and research.¹

Judgment needs to synthesize diverse and often vague or uncertain elements so that practical action can be taken. It cannot wait for circumstances to be ideal or certain. It must work effectively in context even if the way it works may seem "inefficient" from a theoretical or formal point of view.

¹ This is not to say that engineering judgment and consequently practical experience are equally important in all aspects of civil engineering or even of construction. The pilot study itself suggests degrees of importance depending on the tasks in question. Some aspects of geotechnical engineering require highly formalized knowledge of soils and groundwater modeling. In construction certain methods are formally accepted. But the area where engineering judgment was said to be necessary was the decision of what should actually be done on the job site, whether it was the judgment by the superintendent of equipment to be used or the judgment of the geotechnical engineer of what soil variables to use for modeling the specific site and how to react to conditions encountered in the field once construction began or the judgement of a construction project engineer or manager of how to approach the overall accomplishment of the project. Often judgments seemed to be linked to process (perhaps the soil variable judgment is an exception), to a dynamic rather than a static problem.
Engineering judgment is the decision of what to do in specific circumstances to effectively accomplish a practical goal when the theory or formal knowledge does not perfectly indicate what must be done. Since theory is by its nature an abstracted or formalized knowledge it does not clearly spell out every eventuality; engineering judgment is always needed to some degree in any instance of actual practice. In certain, relatively simple practical tasks or portions of tasks, every eventuality may be able to be spelled out and a solution to each formulated, creating a sort of manual or "cookbook," but construction projects, and heavy construction projects in particular, quickly become much too complex for this approach. While it is helpful to continue formalizing portions of the construction process, to the degree that projects are unique, environments unpredictable and human beings are human, engineering judgment will have to be applied. And as long as this is true, such judgment will have to be developed, in the only way it can be developed: through experience; and in the only subject that can effectively and efficiently synthesize the diversity and vagueness of experience: the human person.

Learning about and acquiring technology. The case study of a construction firm described in Chapter IV indicates that construction companies acquire technologies in a project-
oriented fashion: when a particular project requires something they will look into it.

This concentration on the project produces a particularly "instrumental" attitude toward technology in the minds of construction professionals. A principle characteristic of the project-oriented approach is that technology is subordinated to a more strictly instrumental role rather than pursued as valuable in itself. Construction professionals tend to be very much oriented toward solving the technical "problem" at hand. Technology, along with labor and management skills, is seen as one element of the solution, one means to an end. This tendency in construction has been noted by Tatum (1987). In this approach it is not the innovativeness of the technology in itself that is important, but rather its effectiveness. There is no advantage to pursuing "newness" per se. In fact, the issue of innovativeness is so foreign to the minds of many heavy construction professionals that they sometimes do not even recognize when they are doing something out of the ordinary — they perceive their innovation as merely the logical solution to the problem and constraints at hand. Perhaps in industries with more formalized processes the role of technology is more easily isolated and pursued as if it were an end by those in the firm entrusted with this aspect of the process. For construction, since the process is not formalized, it is impossible to isolate technology from its
context so technology continues to be perceived as tool/instrument.

The results of the POS, NS and JVB case studies affirm the project-orientedness of education about and development and acquisition of technology in construction. They also show that this project-orientedness exists in a non-geotechnical project, the Jamestown Verrazano Bridge. Perhaps the project-oriented acquisition of product technologies is brought out even more clearly in the NS case study where a material (polymer) and two kinds of equipment (forms and earthmovers) were acquired by the contractor just for this particular job, not as an investment that may reap benefits over many jobs. At JVB a whole system or process including precasting, post-tensioning and lifting of bridge segments, was developed and acquired for that particular project.

Improving or developing technology. To really develop technologies that work they must work in context, in projects, so incremental improvements are made to bring technologies to this point. For instance, the geotechnical engineers pointed out that the measurements required to develop their discipline must be made under field conditions and therefore it is importance to monitoring a project both for the its own success and for the development of more understanding.
Development of process technology. The importance of contextual knowledge in the conceptual framework of technological development may also explain the emphasis in the interviews on development of process as opposed to products on the construction site. One interviewee says that the input of the contractor is mainly to the efficiency of construction. This requires knowledge of the actual construction technique, the process for producing the product. This is difficult to transmit verbally. Words (and drawings) do not convey process well; they are static, process is dynamic. It can be conveyed to a certain extent in writing but this tends to be inefficient and ambiguous. The most efficient and effective way to communicate knowledge about process is through witness of, or better yet, participation in, the process, i.e., experience or at the least (interactive) simulation, a dynamic means of communication. This would explain the use of simulation in pilot and driver's education as well as apprenticeship in construction trades.

Learning about technologies and acquiring them are project-oriented (contextual knowledge based) activities for both products and processes. But in the area of development of technology, the case studies show processes being developed, modified or perfected on projects and as a result of the particular demands of those projects.
Product technologies, on the projects studied, came from specialty contractors and suppliers who would certainly take into account what they learned on each project, and may modify their products accordingly, but no such development was mentioned by these specialty contractors (though one, at JVB, mentioned having to make modification to his process).

The appropriateness of the conceptual framework for describing the development of process technologies may also indicate that it is more appropriately descriptive of general contractors than of specialty contractors who often have special products along with special processes. This is suggested by interviews with three specialty subcontractors who all develop their own equipment in-house. This presence of in-house R&D (even if it is done by a parent firm) distinguishes these specialty contractors from the general contractors interviewed, none of whom performed R&D in their firms. Specialty contractors may follow a dual pattern of development of technology. They may rely on contextual knowledge for the development of their processes and thus perform this development through project-by-project experience, and rely on more formal knowledge and corresponding formal programs of research and development for the development of their products. Specialty contractors may also have closer ties to manufacturers, a point not pursued in these interviews.
Nevertheless, a few words can be said about the roles of construction participants in technology-related behaviors.

**Role of the general contractor.** In both the acquisition and development of technology there appear to be two general roles. One is the more “active” role of the one who pushes the use of a new technology. In the POS project this role was played by the owner and to some extent the designer. The designer may promote the use of a new technology to fulfill his responsibility for the overall solution to the problem, i.e., the project (a project is an attempt to solve a problem.) He must consider the various alternatives and even the constructability of the various designs and what kinds of construction techniques are available and feasible. For this part of his work he may gather information from contractors (through pre-construction interviews or some sort of review team including contractors) but the designer is still the active participant in the search for appropriate technologies and the main decision-maker (along with the owner.) The contractor, on the other hand, played a more passive role, accepting the decision regarding the major technology to be used and doing his best to implement it.

On the NS and JVB projects the designers did not appear to be the source or impetus for innovative ideas. On the contrary, on the NS project the designers appeared to be
rather conservative and careful. In both projects the general contractor proposed the use of more innovative approaches to the job: polymer slurry and a newer concrete forming system on NS and precast segmental construction on JVB. Thus it appeared that the general contractor was a more “active” promoter of innovation. But this is only at the level of the contractor’s bid for the job. In both projects the innovative proposals were originally made by specialty contractors to the general contractors. These specialty contractors present their particular approach to those general contractors who plan to bid for the job in hopes that several of these contractors will adopt their method and they will have a better chance at being involved with the project. From this point of view the general contractor still has a very “receptive” attitude toward technology. Rather than seeking out or developing better approaches he lets specialists sell their approach to him. Then, if this new idea promises to help him get the job and complete it with relative ease and security as well as a better profit, he will adopt it into his bid.

The contractor plays a role which was less active but just as crucial for the successful use of any innovative technology. While he does not invest much in the search for and in learning about various alternatives nor perhaps in the final decisions about which will be used, he does make a two-fold contribution. First, he must provide the
ability to carry out all the standard construction tasks well, those things which would be common to all projects: scheduling, labor and equipment planning and any particular technical tasks like placing concrete, etc. that may pertain to his work. The second contribution is an openness or receptiveness to innovation that is especially manifested in a professional attitude of cooperation with the other participants. It is the contractor's strength to be generally competent and cooperative, flexible even, so that he can implement whatever design solution is proposed. Thus a "bad" contractor when it comes to innovation is one who is not flexible enough to accept new approaches. The "good" contractor, in addition to the standard skills he must have, acquires and maintains flexibility and openness to innovation. Some means of maintaining flexibility include keeping informed of current and developing technologies through the trade literature, attending conferences and even visiting other project sites, suppliers and projects abroad. The contractor who fails to do these things to a degree commensurate with the size and type of his work will become rigid, narrow-minded and "brittle" so that designers wishing to try new technologies will be unable to work with him.

The general contractor's receptive role is also important with respect to specialty contractors. The roles of general contractor and specialty contractor in NS and
JVB represent a classic division between generalist and specialist: the specialist perfects one small part and the generalist is responsible for making sure it fits effectively into the whole. This division also reflects the importance of context in construction. A specialist develops a part in relative isolation from context so that he can perfect it, drawing out or formalizing, the principles of operation which are independent of context. Yet the part is meaningless without the whole since it was perfected for the sake of the whole. So a need exists for someone to bring the perfected part back into the whole project, someone who has not isolated himself from the specific contexts in which the part must function. This role is filled by the (general) contractor, a role both crucial and elusive in a technological environment which is often so distracted by, if not obsessed with, the perfection of the part.

The general contractor, while playing a receptive role toward technologies in general, does actively engage in the development of some forms of process technology. This active development of technology is related to the general contractor’s responsibility for the efficient and effective running of the overall project. To fulfill this responsibility he must engage in an often forgotten aspect of technological development that occurs on the job site from day to day. Whenever a relatively new construction
technology, whether product or technique, is utilized the contractor usually needs to work out the actual details of its use in the field to increase its effectiveness or assure its practical feasibility. As mentioned in the case studies described earlier in the thesis, a general contractor often needs to "redesign" or adapt aspects of a product or process to make it work on his particular project or re-engineer other parts of his process to allow for a new technology. From this process come incremental improvements in construction technique. They are the result of using the technology and are often passed on through experienced persons. These are the kinds of developments that some firms are beginning to try to keep track of so that they can be passed on to employees working on similar projects.

An economic explanation

While the behaviors observed in this research have been explained in terms of contextual knowledge and the way in which such knowledge, by its nature, must be transmitted, it can be further explained in terms of economics. Two particular aspects of the case study findings are discussed in this section in light of work that has been done that shows the economic factors that influence innovation and communication of knowledge about innovation.
Sources of innovation

The first aspect to be discussed here is the different "roles" played by various construction participants and the relationship of these roles to research done on the functional source of innovation. In certain industries innovations are found to originate most often with a particular industry participant: manufacturer, supplier, user. These participants are defined with respect to their functional relationship to the innovation in question: manufacturer of the innovation, supplier of the innovation, user of the innovation. Which of these types of firms tends to innovate more differs across industries. It turns out that the variations in the sources of innovation can be explained in terms of the potential innovator's relative expectations of economic rents (von Hippel 1990). In other words, the firm that innovates will be the one that expects to reap considerable economic benefits from the innovation.

Recall from the case study of a construction firm as well as the other case studies that comprised the research project describe in Chapter IV, that there appeared to be a variation in the sources of innovations within the construction industry. Product technologies (materials, equipment, components) where innovated by manufacturers or suppliers and process technologies by contractors. In the later case studies (Post Office Square, North Station and
Jamestown Bridge) specialty contractors were found to develop special processes and equipment but not materials used in their processes and general contractors developed processes but neither equipment nor materials. Such variations could also be explained by the different expectations of economic rent for firms fulfilling different functions in construction.

While the present research does not fully demonstrate the applicability of this explanation, it is strongly suggested. This can be seen by consideration of the two conditions set forth by von Hippel for the applicability of this hypothesis (that the innovating firms will be those expecting a considerable economic rent from innovation). These conditions are that: 1) it must be difficult (expensive) for innovators to adopt new functional relationships to their innovations and 2) innovators must have a poor ability to capture rent by licensing their innovation-related knowledge to others.

The first condition, difficulty of changing functional roles, is exhibited in at least one case in the present research, that of the forming systems used at North Station. Although the manufacturer of these forms does have a patent on them the contractor on the job stated that it would be easy to get around it with small changes. Rather, protection of the innovation comes from the capital expenditure required
to provide such a system. This entry barrier most probably exists for many instances of equipment innovation. So for a general contractor, switching from user of the equipment to manufacturer of the equipment is difficult. In turn, it would be difficult for a manufacturer to switch to general contractor, at least for large complex projects, because he would lack the experience necessary to manage such projects. It would be interesting to further investigate specialty contractors who, in the present case studies, indicated that they do develop innovative equipment. How is their relationship to the equipment and the entry barrier described above different than that of the general contractor? Does the specialty contractor really manufacture the equipment or does he work with a manufacturer or is he a subsidiary of a manufacturing firm? Perhaps a manufacturer can switch easily to specialty contractor because of the relatively large amount of formal specialized knowledge required and relatively small amount of general experience. The specialized knowledge may be easier to acquire. These questions were not explored in this research but could be in order to expand our knowledge of the economic influences on innovation.

The second condition is that innovators must have a poor ability to capture rent through licensing. Again, the North Station contractor’s comment that a manufacturer’s patent was not particularly effective is pertinent here as is the
Jamestown Bridge construction manager’s observation that only once in 40 years did he observe a contractor pay a royalty for using a patented technology. From the project described in Chapter IV there was one instance of use of a patented technology for which a royalty was supposed to have been paid but apparently was not. This suggests that it is difficult in this industry to enforce such arrangements. As for keeping certain knowledge as a trade secret and possibly licensing it, this does not seem possible in construction either, particularly with respect to process technologies. The construction process takes place (generally) in a very public way. As one interviewee stated, as soon as he does something new everyone knows about it. They cannot usually be hidden from public view.

Thus the present research gives some indication that the conditions exist for the source of innovations in construction to be explained by the expected economic rents from the innovations for the functional roles of user (contractor) and manufacturer. What this would mean is that firms in a particular functional relationship to a potential innovation will innovate if its functional relationship puts them in a position to reap economic benefits. Construction equipment is often too expensive to reap benefits merely through the use of the equipment unless one uses the same equipment frequently. Thus general contractors who will only use special equipment (like the SLGP earthmovers at North
Station) infrequently will not find it worth their while to develop them. A manufacturer, on the other hand, may benefit much from selling the equipment to many contractors who need it or even leasing it or, as in the case of the SLGP dozers, selling it to the contractor with "guaranteed buy-back" agreement. A specialty contractor, also a user, may innovate in the area of specialty equipment because he will use it often enough to expect sufficient economic benefits. This accounts for the availability of product technologies to general contractors through normal market mechanisms (purchase, lease, subcontract). Those who stand to benefit from innovation in these technologies are those who sell them more than those who use them.

**Informal know-how trading**

Interviewees revealed that some form of informal trading of know-how occurs among firms in the construction industry. This know-how is practical knowledge possessed by experienced individuals concerning how to make a process work efficiently and effectively. Contractors develop a lot of this kind of knowledge which is specific to the particular types of projects with which the experienced engineer is familiar. From the interviews it appears that the way in which trading of this knowledge occurs is through site visits to construction projects of competitors. It may also occur through firms working together on projects as joint venture
partners, general contractor and subcontractors or, as in the case of Jamestown Bridge, as construction manager and general contractor.

Once again, looking at the conditions necessary for know-how trading, we find good indications that they exist for construction know-how. These conditions refer to characteristics of the know-how itself: 1) that it is not vital to the firm and 2) that it can be independently developed by any competent firm needing it, given enough time and money (von Hippel 1990). Such know-how is usually concerned with making a construction process proceed more efficiently. It is not vital because the contractor could achieve the effect he wants with a less efficient process. It is also true that any competent contractor could develop a more efficient process with enough time and experience. It may also be that telling or showing someone does not actually fully communicate the experience itself. People still have to gain experience through practice. Also, even if they not only told others but even showed them or took them through the steps of the experience they still would not be losing much. The reason for this is similar to the reason that know-how trading occurs so freely in other industries. If someone is asking you about something so specific or unique that it requires your special experience, then this indicates how close they already are. They probably already have the project; you are not in a position to gain the job then
because of your experience. Also, they will not lose the job (probably) for lack of experience. They are already close enough to be able to ask such a specific question so it is only a matter of time and expediency. You could refuse to help but they would figure it out eventually. And if you do help you put yourself in a position of being "owed" a favor and others will be more willing to help you expedite your work when necessary.

Remember that one contractor interviewed offered a qualification regarding the trading of know-how. He said that such trading usually occurs after a job has been bid, not before. The information will not help a contractor get the job but once he has the job the information will help him do it. If this turns out to be generally true in construction then it corroborates the statement that know-how is only traded when it is not vital to the firm. If the firm possessing the know-how is bidding on the same job as the one requesting the know-how, then this know-how becomes vital until the job has been awarded. This distinction indicates an economic reason for know-how trading. Know-how is traded when a firm can expect some benefit from it (future know-how gained in return that contributes to a more efficient and therefore more profitable project later on) and it is not traded when a trade would effect an economic disadvantage (possible loss of a new project).
Conclusion

As stated earlier, the conceptual framework developed above will apply to a sector of construction to the extent that that sector fits the description of the nature of the industry: lack of formal body of knowledge to describe the process, one-of-a-kind products and complex, diverse environments. Heavy construction, for instance, would fit this description more closely than some kinds of housing or plant construction.

With respect to technological development the conceptual framework applies more to processes than products. Products can often be developed according to the more formal models of other manufacturing industries, through more formal R&D laboratories. This is because the interface between a product and the construction environment and the precise way that a product fits into the constructed facility can often be well-defined. This definition of interface allows the product to be somewhat isolated from context; it can become an interchangeable part in diverse construction projects. Processes, on the other hand, unless they can be embodied in products, usually have to respond to the peculiarities of each project: its schedule, weather, configuration, labor situation, available equipment to carry out the process, etc.
In summary, the Post Office Square, North Station and Jamestown Verrazano Bridge case studies reinforce the idea of the project-oriented, instrumental attitude toward technology in construction and the consequent reliance on contextual knowledge, while more clearly defining where this attitude and knowledge operate. Learning about and acquiring both product and process technologies takes place in a project-oriented fashion for the general contractor. Development of technology, on the other hand, may be project-oriented and dependent on contextual knowledge with respect to process technologies and not so much with respect to product technologies.
Chapter VIII

CONCLUSION

Benefits of conceptual framework

The primary purpose of this conceptual framework is to better understand the communication of knowledge and the development of technology in construction. This section outlines the benefits or contributions which can be expected from this better understanding. Some examples are given of how the findings presented here might be applied by construction companies and university programs related to construction.

Management of technology

The construction professional will be interested in the management of technology for the effective and efficient completion of projects. The issue of technology management
involves to a large extent questions of communication. Due to the loose and fragmented structure of the construction industry and the craft nature of much of its current technology a large proportion of the communication takes place through relatively informal channels. Often the information itself is not well formalized explicitly. One such type of information is that which is learned through experience by individuals and by the groups of individuals comprising a firm. To the extent that this is the case, the types of management tools most effectively employed in fostering technological development will be those that concentrate on the people in whom the experience-based knowledge is embodied. Thus education for knowledge and training for skills will figure as important elements of management strategies to develop more skill knowledge about construction technologies as will the development of more efficient ways to transfer such knowledge from project to project.

It would be valuable for management information systems to coordinate feedback on what works and what does not work on various projects so that this data could be incorporated in the planning and design of future projects. Needless to say some of this is done in current systems but much pertinent information still resides primarily in the experienced persons and may always do so. The job of management systems may be more as a tool to these persons and
others to find each other when specific experiential knowledge is required. Construction companies could have an experienced person visit sites on a regular basis to pick up on new methods developed on projects and have those who developed them give seminars and visit other sites. Top management could more actively promote site visits of the firm's personnel to the firm's own projects to spread know-how within the firm. They could also encourage site visits to other firm's projects to gather general information about the state of the art even when it does not appear to be immediately relevant. If they wait until it is immediately relevant, for instance when a similar job is out to bid, it may be more difficult to get access to the sites.

Coordination will need to be facilitated not only within a firm but between firms; how a contractor's knowledge about constructability could be better incorporated into planning and design, for instance, is a perennial problem. Designers and contractors could establish "exchange programs" in which personnel would spend some time in each other's firms learning its processes from the inside: how information flows and decisions are made, the points in the process when input from one function (design or construction) would be most helpful to the other function. Builders and designers who specialized in particular types of facilities may find this especially helpful. In particular this type of "exchange program" would be useful for firms that usually do
public work in which the builder and the designer can not work together during the design phase since the construction must be bid separately once the design is complete. Instead of having immediate knowledge of the present project (which would be the ideal situation from a contextual knowledge point of view), each could draw on the experience it gained in previous exchanges with firms that do similar work.

Making people become more explicitly aware of their own and others’ expertise will make contextual knowledge somewhat more accessible. Companies could have personnel explain what they are doing to colleagues on different projects or to students. This forces them to have a more explicit recognition of the processes they engage in to execute a project. In view of the importance of visual presentation and drawing in understanding process, such presentations could emphasize visual means of communication. In-house seminars also promote a general knowledge of who is experienced in which kinds of projects, otherwise only those who worked with an individual might know of his expertise. A related idea is that of peer review within the firm. Designer firms often do this, having older, more experienced designers review the work of younger designers or even just having someone without a personal “attachment” to the designer give it some objective constructive criticism. Builders could do the same with the methods they propose to approach a particular project.
Managers in construction firms will want to find ways to foster the attitude of openness to new technologies that helps them work more effectively in innovative projects. This will certainly entail more and better ways of keeping abreast of technological developments and path-making projects. But it will also require the maintenance of an attitude of openness to new ideas on the part of higher levels of management — willingness to invest in trips abroad or to conferences and conventions, etc. to educate construction managers and not let them be caught unaware by a new technology.

Personnel decisions should certainly be made on the basis of acquired contextual knowledge. A company should keep records of the types of experience possessed by individuals and be careful not to lose valuable knowledge embodied in these people if cuts are necessary. Also, companies can influence the quality of future construction professionals from the point of view of their contextual knowledge by getting involved with education. This will be addressed further in the next section.

Fostering construction's own ways of developing technology rather than trying to make construction conform to a model foreign to it should positively influence the future of the industry. Concentration on the importance of the
transfer of informal knowledge should lead to better coordination of the participants in a construction project while avoiding forcing them into patterns too rigid to accommodate this type of knowledge.

Research and education

Both universities and construction firms have an interest in education and research about the construction process. The question might well be asked though how the conventional R&D establishment, especially the research done at universities, can be effectively tied in with an innovation process that seems to occur largely outside of the norms of that establishment. Certainly the effort to introduce more formalization where it is appropriate and to utilize more scientific advances (for instance in particular materials and components) is valuable. But even to do this effectively requires that researchers know where such efforts are worthwhile and where more practical knowledge is essential.

The key to effective research in the construction industry is a greater understanding of how the whole process of construction actually occurs from identification of a need or problem through design, construction and operation. To do this researchers and professors need to be more organically
linked with the industry. This means not only observing what is done but participating to various extents.

Universities may include practical experience as an advisable or required element of a candidate's qualifications before professorial appointment. Sabbatical time can be spent in industry. Many professors already engage in regular industry involvement through consulting. There is a need for those who are able to abstract and analyze but in order for them to do so they must have the data which is found in the actual industry environment and which is acquired largely through the integrating process of personal experience.

Graduate schools may even consider requiring applicants to have a certain amount of industry experience in order to provide them with some basic experiential data on which to found their research. This approach is not unusual for graduate schools of business. Graduate theses, particularly masters theses but also doctoral dissertations, could be more closely tied in with actual construction projects. The students would then learn to integrate their classroom and laboratory work with the field environment and learn to use the project as a laboratory. In this way graduate students who are planning to become professors will have already begun to have good working relationships with industry and a feel for how to promote and manage cooperative research.
Naturally industry would have to be a willing partner. Companies that get involved with cooperative education programs and summer hiring of students (and professors) are both contributing actively to the education of the students and building up an experienced group of prospective employees. Firms should also provide short term positions for professors on sabbatical or new engineers planning to go to graduate school. Similar arrangements could be made for those researchers working in non-university laboratories. They can also open their projects to graduate students’ and professors’ research. They can make their more experienced personnel available to teach university courses wherein they can emphasize the practical project experience they have gained.

In terms of the content of research, university and industry personnel can work together to set an agenda that promises to produce new technologies that will fit more effectively into industry. For instance, computer aided and automated technologies could be developed not to replace experienced people but to aid them in a more efficient use of their experience. While the university personnel may be more well versed in the specific technologies involved, industry knows what kind of experience its people possess and which must be preserved in the development of technologies. University/industry interaction in both the conceptual design and the practical development of technology will certainly
contribute to a smoother transfer of technology to the field. For instance, a computer program or new machine should be periodically tested during its development in a real project setting by those who are intended to use it. This is a good way of finding out what context-dependent details may have been overlooked in the laboratory work.

Even more formal research approaches are not precluded from consideration. Efforts toward greater formalization of the construction process can be guided by the structure of the conceptual framework in Chapter VII. By centering the framework on the nature of the constructed product and environment and the knowledge that is developed in this environment, it provides some understanding of communication and technological development in any activity that is not highly formalized without necessarily condemning the activity for its lack of formalness and apparent lack of technological development: it is a positive framework. At the same time it gives an idea of how the advantages of a more formalized system can be introduced by showing which elements are key:

To the extent that the nature of construction's products and environment are changed or controlled, knowledge can be more formalized and therefore more easily communicated, which would affect the behaviors indicated. For instance, greater formalization of knowledge could be applied to constructed products or components of facilities that are not so unique
but are repetitious. Also, to the extent that the complex, diverse and unpredictable environment of construction is controlled, more can be learned about the construction process and the behavior of the constructed product which can be isolated from very specific contexts. This control of environment can range from moving work offsite to factories to development of uniform building codes and legal environments. Thus greater generalization and simplification can contribute to the ability to isolate and analyze parts of the construction process. This more formal knowledge will be much more easily communicated so that the industry will not suffer from as much fragmentation: greater formalization allows the development of written and graphic communication that is not embedded in the context of specific projects. Greater formalization of knowledge would lead to more formal R&D programs by industry and a basis upon which construction could take advantage of research and formal educational and analytical methods used in other, more formalized, fields.

Further study of this conceptual framework of technological development can lead to an understanding of how formal and contextual knowledge work together. Innovation may be precisely the kind of human activity that shows up this relationship most clearly. Successful innovation requires both a "good idea" and practical implementation. Sometimes the question arises whether basic science or more practical development is the more crucial element for
successful innovation. It is most probably a combination of the two over time that produces a healthy pattern of innovation. Witness the number of stories of good ideas that did not make it on the market because of the lack of understanding on the part of those developing it for the context in which the innovation would be used: preferences due to culture or fashion, usage in combination with other technologies, etc. These factors are usually difficult to formalized and can often best be known by individuals who have a "feel" for market preferences and what causes them. On the other hand, an innovation may fit quickly and well into an actual market situation but be a dead end, failing to give rise to other innovations or improvements in itself. This may be due to a failure to develop the innovation with a formal understanding of the system in which it works and the intrinsic developmental logic of that system.

Another reason that the formal vs contextual knowledge issue is particularly relevant to the study of innovation is that the very process of innovation seems to die if it is reduced just to that part of it that has been more or less formalized. If we manage innovation solely according to the formal models of innovative behavior that various researchers have devised precisely what we are leaving out in leaving out the "mysterious" or less formally understood part may very well be the most creative part of innovation. Scientific studies should recognize their own short- and long-term
limitations. This means that a certain amount of the innovation process should be managed according to formal principles and that a certain amount may have to be explicitly left up to the apparently ad hoc synthetic procedures characterizing contextual knowledge. The trick is to know where one kind of management begins and the other ends, a knowledge which in itself is probably contextual and experience dependent.

**How broadly the conceptual framework might be applied outside of construction**

The data which the construction industry would yield regarding the development of technology promises to be rich and under appropriate analysis could contribute significantly to our overall understanding of technology and its influence in our society.

It appears, from the data of three case studies, that the conceptual framework of the role of contextual knowledge applies most accurately to the development of process technologies. As such it is not really a model of development of construction technology per se nor of the attitude of a general contractor per se. Rather, context is crucial for effective implementation, for the procedure or process. The more complex and potentially varied the contexts can be, the more dependent process technology
becomes on contextual knowledge because process will interact with context more directly than product (products can be developed with a fairly well-defined interface with contexts). The conceptual framework then applies well to construction, and particularly heavy construction, because this industry does deal with complex and ever different contexts. The conceptual framework will also apply particularly well to the attitude of the general contractor since his is the role of determining an effective and efficient process of implementation, responding directly to all the elements comprising the context of a given project (weather, site conditions, owner's concerns, available labor pool, etc.) The general contractor's project-centered concentration on process would then affect his approaches to learning about technologies and acquiring them, both of which turn out to be project-oriented as well.

Nevertheless, if the conceptual framework is more fundamentally descriptive of the development of process technologies, it is potentially applicable to other participants in construction, to other sectors of the construction industry and to other industries altogether, inasmuch as they may also develop process technology in response to complex and varied contexts.
Future research

As yet the actual details of the processes of technological development in construction are not well known or understood. It will be important to understand them better in order to use them well and improve them. Otherwise we may run the risk of changing or weakening effective processes of development by forcing the industry to conform to a standard that is not appropriate to it. Rather we must discover how to strengthen the processes that work in construction. This will require research on several fronts. One is the investigation of the actual mechanisms of technological development in various sectors of construction. This will entail studying not only the technical, economic and institutional factors affecting innovation but also the human behavior and attitudes, areas that require research methods which may be unfamiliar to engineers. Analytical methods will need to be developed which manage to avoid losing the valuable informal data from these social or human-directed research methods.

Some specific areas of further research include:

- More detailed investigation of the actual mechanisms of technological development in various sectors of construction.
• Comparison of the development of construction's product and process technologies to ascertain the relative importance of contextual knowledge in each.

• Investigations of technological development in other industries to see if the conceptual framework of contextual knowledge can be used to explain behavior, particularly regarding process technology, in these industries.

• Testing of the economic factors which may cause particular construction participants to be the sources of certain types of innovations and which determine the conditions under which informal trading of know-how will or will not take place.

• More research in the area of know-how trading in construction, particularly on the role of site visits and joint ventures (and other instances of working together on the same project) as means of trading know-how and on the timing of trading activities with respect to bidding for new jobs.

• Analysis and further definition of engineering judgment, how it is acquired and used in construction.

• Study of the use of real world engineering projects in graduate students' research and how such
industry/university cooperation may affect both formal education and contextual learning.

- Historical studies of the development of engineering disciplines and the industries that accompany them and their relationship to development of formal bodies of scientific and engineering knowledge. What is the path from contextual to formal knowledge?

- Philosophical studies of the epistemology of technology. What is the relationship between formal and contextual knowledge? Is there a philosophical basis for such a distinction? What practical norms for guiding technological development, including ethical and social norms, could be drawn from a study of the nature of technological knowledge?

Summary

Construction does experience technological development as evidenced by the performance of the heavy construction sector in challenging situations which require technological solutions. Its methods of fostering innovation differ from those of more R&D-intensive industries. Its information transfer is more flexible and informal than formal, its technological development more based on experience than
science and its methods more dependent on people than on systems or ideas.

In particular, the technology-related behavior — education about and acquisition and development of technology — exhibited by the construction industry is reflective of the strong role of contextual knowledge (knowledge intimately linked to the context in which it is acquired) in the industry. The Post Office Square parking garage case study brought out the importance of the project as the context in which this contextual knowledge arises.

The North Station and Jamestown Verrazano Bridge case studies reinforced the idea of the project-oriented, instrumental attitude toward technology in construction and the consequent reliance on contextual knowledge, while more clearly defining where this attitude and knowledge operate. Learning about and acquiring both product and process technologies takes place in a project-oriented fashion for the general contractor. Development of technology, on the other hand, may be project-oriented and dependent on contextual knowledge with respect to process technologies. This project-centered, contextually based development of process technologies applies equally to specialty contractors as to the general contractor.
The conceptual framework of the role of contextual knowledge applies most accurately to the development of process technologies because context is crucial for effective implementation: for the procedure or process. The conceptual framework applies well to construction, and particularly heavy construction, because this industry does deal with complex and ever different contexts. The conceptual framework will also apply particularly well to the attitude of the general contractor since his is the role of determining an effective and efficient process of implementation. Nevertheless, if the conceptual framework is more fundamentally descriptive of the development of process technologies, it is potentially applicable to other participants in construction, to other sectors of the construction industry and to other industries altogether, inasmuch as they may also develop process technology in response to complex and varied contexts.
REFERENCES


Center for Construction Research and Education (CCRE), Construction, "Interview with Dr. Harold K. Forsen, Bechtel Corporation," Massachusetts Institute of Technology, Fall 1990.


Institute by The Cambridge Group, Chapel Hill, NC, September 1990.


Johnson, Edmund G. and Schoenwolf, David A., "Foundation Considerations for the Expansion and Renovation of the Hynes Auditorium," Civil Engineering Practice, Boston Society of Civil Engineers Section, ASCE, Fall 1987.


Rhode Island Department of Transportation, Jamestown Verrazano Bridge Newsletter, Volume 1, Number 1, published for RIDOT by Perini Corporation, Construction Manager, Fall 1990.


Rosenberg, Ronald, "Building from the top down is gaining ground in Boston," Boston Globe, June 12, 1989, p. 25.


Williams, John I., "Direct Fixation Track on the MBTA", Massachusetts Bay Transportation Authority, January 1933.

Williams, John I., "Rapid Transit Construction Progress in Boston", a paper for presentation at the 1984 APTA Rapid Transit Conference.
APPENDIX

References to Interviews

The contents of interviews are referred to in the text in the following manner. The first number refers to the specific interview listed below. The number following the period refers to the relevant point in the interview. A letter after this number simply refers to a subsection of that point in the interview. For example, 2.14a refers to an interview conducted with Mr. Blouin and the relevant portion of the interview is part "a" under point number 14. In one case (Mr. Clougherty) two separate interviews took place. The first one is designated 13i and the second one is 13ii.

The numbers of the interviews are numbered as follows:

1. Steve Barlow - project manager, J.F. White, general contractor, Post Office Square (POS)

2. Rich Blouin - project engineer (POS), J.F. White

3. Jim Becker - president of Beacon Construction and head of construction committee for the owner, Friends of Post Office Square (FPOS). Beacon Companies is part of FPOS.

4. Roy Stifler - construction consultant to FPOS

5. Eldon Abbott - project manager with Parsons Brinckerhoff, the lead designer for POS

6. David Schoenwolf - senior engineer with Haley and Aldrich, FPOS's geotechnical engineer; and Mark Haley - vice president at Haley and Aldrich, also involved with the POS project

7. Professor Robert Whitman - Professor of Civil Engineering at MIT, member of the Technical Advisory Committee for FPOS and chairman of the Geotechnical Monitoring Committee for FPOS

8. Thomas W. Harrison - Manager of Projects, Construction/Maintenance Support, Fluor Daniel, Greenville, SC

9. Donna Cusson - Manager of Research and Development, Perini Corporation, Framingham, MA
10. Frank H. Thomas - Vice President, Research and Technical Services, Turner Construction Company, Chicago, IL


12. Andrew Lemer, Ph.D. - Director, Building Research Institute, National Research Council, Washington, D.C.

13. Joseph Clougherty - senior project manager of the North Station Transportation Improvement Project (NSTIP), from the Massachusetts Bay Transportation Authority, MBTA (owner)

14. John I. Williams - project manager, Design/Development; Construction Directorate, MBTA

15. Rory Neubauer - senior project manager on North Station (NS), from Modern Continental, general contractor in joint venture with Ohbayashi

16. David Coleman - The Millgard Corporation, specialty subcontractor for construction of interior caissons on NS

17. William Osler - Advanced Track Products, manufacturers of acoustical track fasteners to be used at NS

18. David Towers - Harris Miller Miller and Hanson, acoustical consultants to the designers

19. Mark Pelletier - project engineer, Parsons Brinckerhoff/Seelye Stevenson (PBSS), joint venture, designers for NS

20. Richard O'Brien - project manager for NS, PBSS

21. Nino Catalano - vice president, ICOS Corporation of America, specialty subcontractor for perimeter slurry wall and Green Line tunnel portion of NS

22. Warren Pettingell - project manager, Perini Corporation, construction manager for the Jamestown Verrazano Bridge (JVB); senior vice president of Perini

23. Richard Walsh - project manager, Atkinson-Kiewit Joint Venture, general contractor for JVB

24. Michael Veegh - VSL Corporation, post-tensioning subcontractor and lifting contractor for JVB
Site visits are referred to in the following manner:

Post Office Square: POS-SV
North Station: NS-SV
Jamestown Verrazano Bridge: JVB-SV