CHAPTER 2. RELATED RESEARCH AND METHODOLOGY

Our study extends four areas of research: innovation in the Soviet Union, computing in the Soviet Union, Western research on innovation, and organizational development. In this chapter we discuss the literature in these areas, the research questions, the research methodology and the conceptual framework which serves as a platform for the study.

2.1 Technological Innovation in the Soviet Union

2.1.1 Characteristics of Soviet Science

Loren Graham has commented that the Soviet Union was ‘‘a nation with an explicit commitment to science, including a value system and a philosophical world view based on science, which is unmatched in intensity by any other nation in the world’’ [Grah75, 12]. Although Soviet thinking about the role of science in society and the drive towards a communist society has varied since the inception of the Soviet state, it has always figured prominantly. During the 1960s science was given enhanced status when it was declared a direct productive force in its own right, on a par with production, rather than something which lagged behind, and was subordinate to, production. The post-Stalin years saw a rapid increase in the number of researchers and research facilities. Statistics on the number of research personnel are difficult to obtain, interpret, and compare, but many who have examined this question have concluded that the USSR had considerably more people working in research than any Western country, both overall and as a percentage of the working population [Fort90, 8]. High-ranking scientists have enjoyed considerable prestige and benefits in the Soviet society. Science as a whole has been rather well funded for many decades under Soviet rule.

Nevertheless, the Soviet Union trails the United States in many common indicators of scientific performance: number of Nobel Prizes, origin of major breakthroughs, frequency of citation by fellow specialists [Gust80, 31]. Both Western and Soviet writers have for many years been critical of the Soviet Union's inability, with some exceptions, to generate world-class research results and innovations, and see the latter through into production and use within the national economy, particularly from the 1960s to the present. (See [Fort90; Nolt88] for references to this literature.)

A number of researchers have identified some of the general features of Soviet science. Thane Gustafson describes five dominant charateristics: 1) Soviet pure science is strongest in fields that depend the least on material support (instrumentation, sophisticated materials, and equipment); 2) Soviet science is often slow to accept radical conceptual changes or take up new approaches; 3) in several fields, Soviet scientists have achieved results through long-term efforts in traditional specialties and established methodologies; 4) when they do make crucial breakthroughs, Soviet scientists are often unable to maintain their lead; 5) Soviet science holds leading positions in fields that enjoy high-level attention [Gust80, 32-33]. Others focusing more on applied research point out the long implementation cycles, weak links between science and production, the reluctance of industry to use the results of science, the relative isolation of the Soviet scientific community from its Western counterparts [Fort90].

2.1.2 Analyses of Innovation in the Soviet Union

Western and Soviet scholars have identified numerous factors which have contributed to the state of Soviet science and its ability to produce quality, useful results. Joseph Berliner's study on the decision to innovate in Soviet enterprises was the first in-depth look at the question of innovation in the Soviet context [Berl76]. Berliner does not attempt to explain fully the rate of innovation throughout the entire economy, or the genesis of innovation itself. Rather, he focuses on the civilian industrial sector and deals with the factors which affect the assimilation of new products and processes into production, rather than those that impact the earlier stages of technological process [Berl76, 3]. Neither does he address questions of economic and science policy, the technical characteristics of society such as tastes and values which influence demand, or historical or cultural influences. The four structural properties of the economy which he examines are prices, rules which guide decision makers, incentives, and the organizational structure of the economic system as a whole [Berl76, 12]. Organizational structure includes both the units that comprise the system and the ways in which they relate to one another [Berl76, 29].

In a series of two volumes [Aman77; Aman82], Amann and Cooper have assembled a number of case studies examining the technological level of various branches of industry and technological innovation within the Soviet Union. These volumes have tried to provide a greater level of detail about the technological level of Soviet industry, and address what they feel is a weakness of the general surveys–their tendency to present general patterns which reveal little of the patterns of variation between industries, and their emphasis on national policy and planning or on the individual enterprises with little exploration of the intermediate relationships between the ministries and their subordinate research and development institutes [Aman82, 8].

The Berliner and Amann and Cooper studies complement each other, and provide a solid view of technological innovation under the pre-*perestroika* system. Much has changed since 1985, however, and a goal of our research is to examine how the process of technological innovation has changed, within one sector. [Aman82] and [Berl76] suggest that given the changes observed in the Soviet Union, one might reasonably expect to see significant change in the process of technological innovation. In his introduction, Amann comments that ‘‘[a]bsence of competition and user feedback represents perhaps the most potent single factor inhibiting the pace and scope of innovation in the USSR’’ [Aman82, 12,254]. Berliner suggests that ‘‘[a]ny structural reforms designed to accelerate the rate of innovation must therefore alter the traditional balance of reward and risk....The appropriate alteration of the balance of risk may be accomplished by a structural change designed to increase the degree of enterprise autonomy over its transactions with other enterprises and organizations'' [Berl76, 522]. Hage calls the amount and variety of strategic decisions made by members of the organization organizational autonomy and regards it as a significant variable [Hage80, 387]. As we shall see below, the reforms have introduced greater levels of competition, feedback from users, and local autonomy. Are these changes bringing about the improvements in innovation predicted by Berliner, and Amann and Cooper?

Other researchers have examined innovation as part of a broader look at scientific research and development as a whole, within the Soviet context. Many features of science more generally and technological innovation in particular are directly or indirectly related to the centralized nature of the management of the economy. While it is generally not the case that science projects are determined in a ‘‘top-down’’ fashion with individual scientists having little input in the planning process [Fort86], the Soviet system was characterized by vertical administrative controls which strongly affected the allocation of resources, the inter-organizational coordination, and the indicators and incentives which shape R&D and production. Bruce Parrott describes some of the administrative rigidity of the management of science even during the 1960s and 1970s when efforts were being made to decentralize somewhat the highly centralized system inherited from Stalin [Parr80, 75]:

> Administratively, all changes in the internal structure of individual scientific research bodies continued to require the consideration and approval of their ministerial overseers. Financially, research units were asked to submit highly detailed annual budgets, and once these estimates were approved, transfers among budgetary categories on the units' own authority were not permitted. In addition, these estab-

> lishments depended on centralized material-technical supply; they could not, without higher approval, sell or trade equipment that was no longer useful to them. Finally, in selecting research topics, each unit had to submit for the confirmation of its superior ministry or department a thematic research plan that specified most of the research to be undertaken in the coming year.

Besides limiting a research institute's ability to respond in a flexible manner to changing research conditions or advances in the field, such an arrangement can greatly increase the length of research cycles. Needs must be specified months or years in advance with little guarantee that they will be fulfilled. It is difficult under these circumstances to make changes–to acquire unanticipated supplies or equipment–in the middle of a plan period [Gust80, 52].

The centralized, directive-planning system does more than reduce the flexibility of individual organizations; it can also skew a research effort away from providing the ''best'' results under a given set of circumstances. One characteristic of the Soviet system of economic management was the use of a variety of indicators by which to measure progress and the fulfillment of plans and goals. Alec Nove has identified the fundamental problem with using quantitative aggregates (tons, meters, rubles, numbers of units, etc.) as indicators [Nove86, 75-112]. If a quantitative aggregate is used to measure success or failure, it tends to distort the production process in favor of this indicator. For example, if the primary indicator is numbers of microchips manufactured, then reliability is likely to be sacrificed to meet the target plan. If the total value of output is the primary indicator, then the product mix is likely to shift in favor of the more expensive products, etc. Aggregate indicators cannot give the proper priority to all necessary product parameters at the same time without overwhelming the planning process with information.

In practice, although multiple indicators were included into a given plan, some indicators were understood to be more important than others. Thus in scientific research, providing a finished piece of successful research was often less important than making sure a given amount of money was spent on research in a specified timeframe [Fort90, 133]. The plan would be fulfilled when the money was spent, not when a successful result was delivered. To be sure, this picture is oversimplified and results were not unimportant, but the overall effect of many of the planning mechanisms was the decoupling of funding and provision of inputs from the provision of high-quality research, and to substitute easily-measured indicators in place of research ‘‘success’’ (something very difficult to measure in the abstract).

Traditionally, the argument for centralized management of science has centered on the ability to concentrate resources on priority projects and to reduce duplication and waste of effort. As Parrott notes, such management has a number of weaknesses, including the possibility that the administrators do not have the expertise necessary to make the best allocation of resources or evaluate the return from such allocation, the elimination of competition which serves as a powerful motivator in the West, and the reduced flexibility and ability to respond quickly to new developments [Parr80, 72-73].

Another consequence of the hierarchical nature of the Soviet economic system was departmentalism (*vedomstvennost’*). The lines of authority, planning, and resource allocation ran vertically, from enterprises and institutes up through their respective ministries. Horizontal links between organizations typically were established higher up in the hierarchy. The greater the ‘‘administrative distance’’ between two organizations, the higher one needed to go in the respective hierarchies to establish contact. Departmentalism tended to make links between players in the development and supply cycles longer, more rigid, and on the whole less efficient.

Departmentalism has been a particularly strong factor in the relationships between Academy research institutes and ministry production facilities. During the early 1960s, in an effort to delineate more clearly applied and fundamental research, many production and applied R&D facilities were transfered from the Academy to industrial ministries. Ideally, under this arrangement, Academy institutes would transfer their results to industry, at which point industrial design bureaus would advance the technology to the point of series production. In practice, the Academy typically encountered resistance to its results by the ministries, from the production facilities, branch science, and especially the lead institutes in branch science [Lakh90, 40]. Lakhtin summarizes the most significant reasons for this state of affairs [Lakh90, 42]. Among them are the ‘‘not invented here’’ syndrome (not uncommon in the West, either) which makes branch science reluctant to invest time, energy, and facilities in furthering Academy projects, the overloading of production facilities with their own plans, and competition with ideas and research directions originating in the industrial ministries.

Lakhtin views the root cause as the lack of an effective, single authority overseeing all of science; in otherwords, insufficient centralization. While the Academy and the State Committee on Science and Technology (GKNT) in principal had responsibility for establishing national research policy and coordinating research efforts throughout the economy, in practice they had little direct influence over ministerial R&D and production facilities. It is not clear that such a single authority would have resolved the problems, however. The experience within individual ministries showed that departmentalism played a significant role even when a single individual, the minister, had authority over the whole ministry. There was always resistance to getting organizations or organizational components to work together when such work ran counter to their perceived interests.

A further hinderance to innovation has been the lack of slack resources. Gustafson points to the lack of instrumentation and adequate supplies as a principal factor shaping the state of Soviet science [Gust80, 48-54]. Clearly, research projects are hindered if high-quality tools and supplies are not available, or require considerable time and effort to acquire. Gustafson cites as reasons for this the insufficient production of supplies and instruments; general lag in sophistication; slow and unresponsive planning of supply; lack of effective communication between users and producers of equipment; and a lack of coordination among industrial ministries.

The Soviets also have provided analyses of the state of their scientific establishment and its ability to innovate and have proposed many measures to improve it over the years. Louvan Nolting has summarized the Soviet perspective in [Nolt88]. Soviet publications suggest five major reasons for shortcomings in the innovation process [Nolt88, 2-4,37-105]:

- There has been a lack of capital investment in the advancement of innovations, limiting the resources available to move an innovation from R&D to production. In addition, depreciation policies designed to extend the use of existing equipment slows the turnover of old equipment. Existing capital has, overall, favored current production over innovations.
- A shortage of necessary input materials to carry out R&D projects hinders both the manufacture of new products and the development of prototypes. Shortages are aggravated by incomplete standardization of industrial items and the low degree of specialization in production, making it difficult either to build new items on the basis of existing technology or to acquire the specialized technology needed for many projects.
- A poor integration of innovation plans with production and other economic plans means that supplies needed for innovation are poorly coordinated, that

innovations which take place are often poorly suited for actual production conditions, and that the various stages of R&D are poorly coordinated.

- Bureaucratic barriers prevent or delay communication between developers of innovation and producers.
- The incentives for production frequently are at odds with those for innovation, causing producers to favor production over innovation.

As Nolting points out, while there is considerable overlap between Western and Soviet analyses of innovation in the Soviet Union, the Western analyses tend to place greater emphasis on problems which they view as inherent in the centralized directive system of economic management [Nolt88, 111]. Generally speaking, Soviet analysts tend to stress the lack of sufficient capital and supplies, and the inefficiency of many procedures needed to carry out innovation [Nolt88, 112]. Implicit is the notion that to improve the state of innovation, one need only make the existing system function better.

2.1.3 Efforts to Reform Soviet Science

So far we have not discussed efforts that the Soviets have made to reform their system to encourage innovation and improve the state of science. Since the Soviet Union was formed reform programs have been carried out on a regular basis to address the problems identified above. These efforts, which we briefly describe below, reflect some of the underlying tensions which have shaped Soviet science as it has evolved. The primary tensions have been between centralized and decentralized mechanisms for managing science, the use of directive versus economic mechanisms as the agents of management, and the balance between fundamental and applied research and which organizations should be responsible for which.

Lakhtin has broken down the evolution of Soviet science into four phases [Lakh90, 6-19]. The first, from the October Revolution to the late 1920s, was marked by efforts to organize science in the service of socialism. Science was not considered a productive force in itself, but rather was subordinate to efforts to increase the means of production. Organizational differentiation was carried out as research institutes were created, and organizations such as the Academy of Sciences were transformed from a ‘‘collection of scientists’’ to a scientific organization with a growing number of research institutes subordinate to it [Lakh90, 8]. Increased emphasis was placed on the training of specialists, with the creation of a system of institutions of higher education (VUZ).

The second stage, from the late 1920s to the mid-1950s, the reign of Stalin, was marked by a sharp move towards a strong form of centralization. The prevaling philosophy was that science was subordinate to philosophy and Party ideology [Fort86, 15]. These years were characterized above all by a very rapid pace of industrialization within the framework of five-year plans. A large number of research institutes were created, chiefly within industry with a strong emphasis on applied research. A characteristic of this period was the drastic absorption of science (as well as the rest of industry) into a centralized directive form of management. For example, 1936 marked the beginning of a sharp decrease in contract work (*khozdogovor*) carried out between a research institute and an industrial customer. In 1932 57% of all research done in branch institutes was carried out under contract; by 1937 it was only 14%. By 1950, 100% of the work of scientific research institutes was financed through the state budget, or 0% under *khozdogovor* [Lakh90, 157].

During the third stage, from the mid-1950s to the mid-1980s, science began to be treated as a direct production force in the national economy and grew into a large branch of the economy. The system of management of science, exemplified in the creation and growth of the State Committee on Science and Technology (GKNT), expanded considerably. Under the campaign for ‘‘scientific-technical progress’’ increasing numbers of large-scale scientific programs were initiated and corresponding super-institutional management organizations and systems were created. New branches of science were created (electronics, atomic energy), as were many new research institutes and research centers such as the Academic City (*Akademgorodok*) in Novosibirsk.

A more scientific approach to administrative science and management of the economy emerged after 1956 based on econometric models, information processing and feedback, and scientific management of labor [Thom83]. Such economic measures also penetrated the management of science with the evaluation of scientific results through the use of economic indicators. Inherent in such efforts was the notion that science was a productive force in the economy and as such a partner to production.

During the third phase of Soviet science, a number of efforts were made to reform the scientific system. During the mid-1950s the ministerial bureaucracy was coming under increasing pressure to speed up the pace of technological advance. Khrushchev’s reforms of 1957 called for a rather drastic decentralization of industry through the transfer of much of the power and personnel of the central economic bureaucracy to regional economic councils *(sovnarkhozy)* [Parr83, 172-177]. Even in their most radical, proposed form these reforms did not achieve significant centralization by Western standards, but science was granted less decentralization than were other parts of the economy. The State Scientific-Technical Committee (transformed into the State Committee for the Co-ordiation of Scientific-Research Work in 1961, finally becoming the State Committee on Science and Technology in 1965) was created in 1957 to coordinate scientific research [Lakh90, 29]. At the same time, a large percentage of R&D facilities in the civilian sector were transfered to the jurisdiction of Gosplan, the State Planning Committee, although

Gosplan soon shifted control of them to other state committees as the administrative load became unbearable [Parr83, 174-175]. Some decentralization had taken place, but without the introduction of incentives at the lower levels of the economy, innovation and R&D continued to lag.

During 1961 the Soviet government tried to increase the low-level incentives for innovation through the introduction of a form of *khozraschet*, or economic self-accounting, and self-financing, and improving the dissemination of scientific and technical information [Parr80, 74-75; Lakh90, 157]. In part, this represented an effort to substitute economic links for the organizational links which had been disrupted by the 1957 transformation of industry from a highly-centralized to a more regional structure. With the rapid growth of the economy and the scientific community, there was a need to try to use resources as effectively as possible, and it was felt that *khozraschet* could accomplish this [Lakh90, 157-158]. This form of *khozraschet*, intended to make research more responsive to the needs of concrete customers, was in effect only at the level of enterprises rather than at higher-level administrative structures. As a result, projects involving multiple organizations and higher levels of coordination were often not carried out on *khozraschet* principals. In addition, the version of *khozraschet* implemented in 1961 involved ‘‘payment for the process’’ rather than ‘‘payment for the product,’’ weakening the accountability of the researchers to the customers [Lakh90, 158]. Finally, administrative controls on budgets, material-technical supply, and organizational structure remained very tight [Parr80, 75].

During the late 1950s fundamental science was also coming under attack for, in particular, the low number of Nobel Prizes awarded to Soviet scientists relative to those of the United States or Western Europe. There was a perception that with the reorientation of science in the early 1930s towards applied research, fundamental research had been neglected. One of the measures taken to increase the relative weight of fundamental science was the transfer in 1961 of 92 Academy of Sciences institutes to the industrial ministries. Not surprisingly, the theoretical underpinings of much applied research was diminished and the Academy lost much of its ability to carry out the prototype development work necessary to pursue avenues of research [Lakh90, 39-40].

Following Khrushchev's ouster in 1964, the Brezhnev administration initiated a broad set of economic reforms, seeking to institute ‘‘scientific decision-making’’ and major decentralization to improve the efficiency of the economy. Spearheading the effort was Prime Minister Kosygin, who favored exposing enterprise and institutes to market forces to make them more responsive to customers. Between 1965 and 1969 a series of reforms were instituted which, in the balance, resulted in greater decentralization of management of science, but which also reflected the tension between proponents and opponents of decentralization. The results throughout this period had a compromise nature, incorporating a mix of centralizing and decentralizing measures.

In 1965 the regional system of economic management was converted back to a branch-ministry system with the abolishment of the *sovnarkhozy*. Responsibility for R&D coordination was brought back more tightly under the control of Moscow-based organizations, and production targets, product-mixes, and inter-enterprise exchange of goods were strongly centralized. As Parrott points out, the decrees at the same time removed a number of ministerial controls and put more emphasis on financial levers and incentives to stimulate enterprise performance [Parr83, 215-216].

Officials in the Academy of Sciences and the GKNT, seeing the increased authority of enterprise managers, pushed for a greater loosening of controls in science as well. Their proposals included increasing the role of contract work within Academy institutes and basing allocation of resources more on competition. These proposals met with opposition both within the scientific community and the government bureaucracy, and the 1967 resolutions regarding R&D facilities also reflected a compromise. Central agencies kept the responsibility of approving research programs for institutes, but the institutes themselves received more freedom in shaping institute staff and in shifting funds among research projects [Parr80, 79-80; Parr83, 223-224; Lakh90, 160]. Profit also became a more important indicator [Lakh90, 160]. The pricing system had a negative effect, however, in that it did not give enterprises enough profit on new products and enabled them to manipulate cost data to obtain high profit levels of the production of products already in series manufacture, encouraging the continued production of the latter rather than introducing new technology [Parr83, 226-227].

Dissatisfied with the progress, the Soviet leadership adopted a wide-ranging package of resolutions reforming science in 1968-1969. The reforms called for the broad-based introduction of competition in R&D, provided for the establishment of personal incentive funds within organizations, created ministerial funds to support projects selected by the technical councils of individual institutes, increased the legal liability of R&D facilities for their contracts.

The *khozraschet* mechanism was further tuned in 1969 with the introduction of an arrangement in which developing organizations could receive a profit of up to 1.5% of the ‘‘economic effect’’ gained from the use in industry of their research results [Lakh90, 161; Parr80, 83-84]. The ‘‘economic effect’’ indicator was largely meaningless [Mche85], but this form of *khozraschet,* involving payment for the process plus a bonus for the effect of the result, was first implemented in the Ministry of Electrical Equipment Industry (Minelektrotekhprom) and later spread throughout industry.

Also introduced in Minelektrotekhprom at this time was a ‘‘Single Fund for the Development of Science and Technology’’ (EFRNT) as an effort to implement a greater concentration and coordination of research funds and projects [Fort90, 134-135; Lakh90, 161]. This system, in which most of branch R&D spending was drawn from a single centralized ministerial fund and distributed via so-called lead-organizations for large-scale projects, gradually gained acceptance and by 1979 had been implemented in all non-defense industries [Fort90, 134-135]. Another measure which provided a counterweight to much of the decentralization that was taking place at this time was the use of the ‘‘program-goal method’’ (*programmno-tselevyye metody, PTsM*) in the planning of science. This method of planning, which was to govern 25% of total scientific expenditure by the early 1980s, was based on the high-level specification of long-range (15 and 20 year) priorities. Like the EFRNT, PTsM was to give central authorities more focused control of projects, but throughout the country rather than in just a single branch. In addition, PTsM sought to overcome some of the lack of integration between research and production plans [Fort90, 135-136].

In a further effort to close the gap between R&D and production, another 1968 resolution was passed creating ‘‘scientific-production associations’’ (NPO). The underlying idea was to combine R&D and production facilities into a single, relatively low-level administrative structure [Fort90, 115-116]. This resolution was implemented slowly. The resolution was largely voluntary (to be taken ‘‘in necessary cases’’). There was considerable room for interpretation in exactly what an NPO was and how large it should be, and a variety of opinions about how much authority they should be given relative to ministries, *glavki* (main administrations), and individual enterprises. Regional officials tended to favor the creation of small associations, as did the GKNT and Gosplan, while the central ministry officials favored the creation of fewer, but larger associations and a more centralized, Moscow-based, form of management [Parr83, 286-289]. In 1973 an attempt was made to break this log-jam in a resolution calling for wide-spread reorganization of industry. It, too, represented a compromise between the centralization and decentralization forces. While most ministerial *glavki* were to be abolished and the association was to become the primary economic unit, the associations would range widely in size and scope of authority. The largest were the all-union associations (VPO) which were to have nationwide authority over their industrial sector and made it likely that there would be little effective decentralization of authority [Parr83, 289]. However, it appears that the NPO were successful in decreasing R&D cycles and increasing the number of innovations generated. In his summary of a number of assessments Parrott points out that by some indications the average reduction in R&D cycle time was 25-30%. Nevertheless, it appears that the overall level of innovation on a nation-wide basis, as measured by the number of new types of machines and equipment created, in fact decreased between 1970 and 1976 [Parr83, 290]. Nevertheless, during the 1970s and 1980s the number of NPO grew sharply, from about 80 in 1973, to 100 in 1975, to 250 in 1985 and to twice that number in 1988 [Parr83, 289; Fort90, 116; Lakh90, 204].

Having been largely stripped of its ability to conduct applied research during the early 1960s, the Academy of Sciences gradually grew more involved in development work during the late 1970s and 1980s. In 1977 a number of changes were made to the Academy's statute which included technical sciences within its sphere of appropriate activities. Subsequently some of the applied institutes were returned to the academy and new ones were established [Fort90, 50]. This trend was to have a significant impact on high-performance computing, setting the stage for a number of parallel-computer prototype development projects.

In spite of the reform efforts mentioned above, levels of technological innovation and implementation remained unsatisfactory. The 26th Party Congress called for enhanced measures to accelerate scientific and technical progress as a key factor in intensifying the nation’s economy. During Andropov’s tenure, on August 18, 1983, a joint Central Committee-Council of Ministers resolution ‘‘On means of accelerating scientific-technical progress in the national economy’’ was issued. Among these measures was the expanded application of program-goal methods in the area of science as a means of converting the 20-year Comprehensive Programs into five-year plans through the use of a hierarchy of all-union, republic, branch, and regional scientific-technical programs [Arkh86, 16; Kush86, 26]; the streamlining of the economic indicators and sources of funding to the components of the NPO; and the initiation of new forms of scientific organization, such as the temporary scientific-technical collectives of which the START new-generation computing initiative, discussed in chapter 6, was the prototype. The resolution also pushed the *khozraschet* mechanism a step further in the direction of ‘‘payment for a product’’ rather than for a process, or a process plus bonus, as had been the case in earlier reform measures. Lakhtin sums up the success of the latter as follows: ‘‘But the implementation of this *khozraschet* principal was bogged down in part because of the lack of willingness of the ministries to lose their traditional control levers, and in part by a lack of the resources necessary with which to get their institutes ready’’ [Lakh90, 163].

In sum, the rather large number of efforts to reform science in the three decades prior to Gorbachev reflect an on-going dissatisfaction with the level of technological innovation and implementation in the Soviet economy, but a considerable lack of agreement among policy-makers about how to best address the issues. Many measures have been experimented with: a variety of *khozraschet* mechanisms, funding systems, organizational structures at all levels, and economic indicators. The reforms reflected the tension between efforts to centralize and decentralize science. The underlying desires to tighten the links between entities in the R&D chain, improve the responsiveness of R&D facilities to the users of innovations, and in general improve the level of applied and fundamental research were addressed alternatively (and often concurrently) by, on the one hand, efforts to enhance low-level responsibility, incentives, and flexibility and, on the other, attempts to add higher level structure, control, and coherence to science on the branch and national scale.

In part, however, the reforms reflect the sometimes conflicting needs and goals of the conduct of science. On the one hand, it was felt that reducing centralized control would improve initative, responsibility, and responsiveness to real-world needs at the lowest levels. On the other hand, conducting scientific projects which are large in scope or effect, which involve the participation of many different organizations as suppliers, executors, or users was perceived as requiring a comparable centralized management structure. The criticism of ''*melkotem'ye*'' (excessive concentration on minor tasks) has been frequently used as a justification for greater centralized funding and control even though small, short-term projects filled needs of both developers and customers [Fort90, 4,92; Lakh90, 147-148].

At all times Soviet science was conducted within the general framework of the centralized, directive system of economic management. The five-year and annual plans continued to provide the blueprints for institute activities and the material-technical supplies needed. A set of state standards continued to dictate the steps to be taken in a research project. One set of standards, formalized in 1973 as the Unified System of Design Documentation (YeSKD), specified the stages of work and the documents to be filed and approved at each stage. Other standards specified the formulas for calculating a variety of indicators, the cost of development and manufacture, etc.

2.1.4 The *Perestroika* Reforms

While the results of any particular reform package are difficult to measure, there is little question that by the time Gorbachev was appointed General Secretary in 1985, the hoped-for improvement in technological innovation and implementation had not been achieved. At the same time, advances in science and technology and their broad application were seen as the cornerstone to a revitalization of the Soviet economy. At the April, 1985 Plenary Session of the Central Committee of the Communist Party Gorbachev stated that

> [t]he task of accelerating growth rates–substantially accelerating them–is completely feasible, if the intensification of the economy and scientific-technical progress are placed at the center of our work, if management, planning, and structural and investment policy are restructured, if organization and discipline are enhanced everywhere, and if the style of activity is fundamentally improved...As a primary strategic lever for the intensification of the national economy and the better utilization of accumulated potential, the Party is bringing to the fore the cardinal acceleration of scientific and technical progress [Gorb85].

To achieve these goals, Gorbachev proposed a multifaceted approach which included both greater centralization and decentralization, increased reliance on economic mechanisms, and the two-pronged advance of both applied and fundamental research. At a conference on questions of the acceleration of scientific and technical progress in June, 1985, he stated that

> [w]e should advance along lines of the further strengthening and development of democratic centralism. Increasing the efficiency of the centralization principle in management and planning, expanding the independence and responsibility of enterprises, making vigorous use of more flexible forms and methods of management, economic accountability and commodity-money relations, broadly developing

> the initiative of the masses–this is the fundamental essence
> of restructuring [Gorb85b].

He called for an expansion of the role of the Academy of Sciences in both fundamental and applied research. He strongly criticized branch science for the low qualitative and quantitative level of its research, and called for greatly increased efforts to include R&D institutes into associations and enterprises, reducing the ‘‘isolation’’ of institutes and design bureaus from production (by March, 1987 the number of NPOs had reached 376; by the end of 1990, 500 [Lakh90, 208]). In addition, he proposed the creation of integrated interbranch scientific and technical centers to coordinate work in key technical areas. In searching for a mechanism which would spur collectives to achieve success in accelerating scientific and technical progress, he proposed a set of measures which would strengthen the customers’ influence on the technical level and quality of output. These included a shift to full *khozraschet* with profit as the primary indicator, a decrease in the number of planned assignments and a reduction in the number of plan indicators. Underlying the measures was the notion of ‘‘intensification’’–that the measures to accelerate scientific and technical progress should pay for themselves [Gorb85b]. In other words, in contrast to past industrialization campaigns, progress would be made not through extensive increases in funding or allocations, but through a more efficient use of the resources already available.

During the following years, many of the ideas proposed by Gorbachev were encoded in law and policy. Among the *perestroika* reforms most strongly affecting science were:

- February, 1986 decisions made at the 27th Party Congress to enhance the role of the Academy of Sciences as a coordinatator of scientific research within the country, strengthening its responsibility for the creation of the theoretical foundations of fundamentally new forms of technology [Lakh90, 46].

- the creation of inter-branch scientific-technical complexes (MNTK) starting in 1986.

The MNTK were intended to overcome the departmentalism between branches of industry and academia and the resulting gap between research and production. They were headed by a major research institute, often from the Academy of Sciences, and contained a number of other institutes, design bureaus, prototype development facilities, and production enterprises, drawn from a variety of ministries. The MNTK have not generally been perceived as successful, suffering from insufficient real authority to compete with the ministries from which the constituent organizations were drawn, weak support from the Academy of Sciences, etc. [Fort90, 118-123; Lakh90, 210-214].

- March, 1987 decree ‘‘On raising the role of VUZ science and the acceleration of scientific-technical progress, improving the quality of training of specialists.’’

Among other things, this decree called for a doubling or trebling of the amount of exploratory and theoretical research done in the VUZy by the end of the 12th Five Year Plan (1990). This was to be accompanied by some additional budget appropriations, but also through an increase in the amount of contract-based funds [Fort90, 92-93]. The intent of the decree was to involve the VUZy to a greater degree in large-scale scientific and scientific-technical problems [Lakh90, 80].

- A decree passed at this time expanded the authority of Academy of Sciences departments, giving them powers previously held only by the Presidium.

These included the right to manage all material and financial resources and distribute them among subordinate institutes, authorize the latter’s plans, establish international contacts, and develop and authorize the basic directions of fundamental research [Lakh90, 44].

- June 1987 resolution ‘‘On state enterprises (associations)’’ [Prav870701].

This far reaching resolution, more than any other, altered the conduct of science within scientific-production associations. To a considerable degree, this was the resolution which gave the proposals advanced by Gorbachev in 1985 and confirmed at the 27th Party Congress in 1986 a legal foundation. In general, it

> ‘‘deepens the principle of centralization in the accomplishing of highly important tasks of the development of the national economy as a whole, provides for the strengthening of economic methods of management, the use of full economic accountability and self-financing, the expansion of democratic principles and the development of self-management and defines the relationship between enterprises (associations) and bodies of state power and management.’’

The resolution established full *khozraschet* as the basis for economic activity of enterprises and associations, making the income earned through contracts the primary source of funding for the various technological development, wage, and social funds. Full *khozraschet* was to penetrate to the lowest levels, that of laboratories, shops, etc. The enterprises (associations) were given considerable rights to keep this income and use it at their discretion. The resolution gave them the responsibility of formulating their own plans and contracts (albeit ‘‘[g]uided by control figures, state orders, long-term scientifically substantiated normatives and ceilings, as well as consumers’ orders...,’’ effectively giving the centralized authorities considerable power in determining the R&D and production schedules.) Enterprises and associations were given the right to give, sell or trade materials, equipment, buildings to each other and establish contracts with each other. The resolution also gave the enterprises and associations the right to determine their internal structure and elect their own executives. Large-scale reorganizations were still subject to the approval or higher-level agencies. Enterprises and associations were given the right to engage directly in joint projects, joint ventures, and commercial activity with CMEA and Western organizations, although these were subject to approval by central authorities.

The resolution did not free prices, or take off all restrictions on wages. Prices on the results of research and development could be negotiated between the provider and the customer, however. The resolution also made it clear that orders from the state had to be fulfilled before contracts from individual enterprises or associations could be satisfied.

In August, 1989, this law was amended to grant structural units and autonomous enterprises belonging to an association the right, by a decision of their labor collectives, to withdraw from the association, provided they observe the contractual procedure and obligations established during the formation of the association. Enterprises and associations could also the right to withdraw from their ministry [Izv890811].

- September, 1987 decree ‘‘On transferring scientific organizations to full *khozraschet* and self-financing.’’

Embodying the notion that a research product is something which can be bought and sold like a commodity, this decree stipulated that scientific organizations were to earn enough through contracts with users to cover their development costs and the associated institutional overhead. Technically, organizations which failed to do so could ‘‘cease to operate.’’

- 1988, introduction of competition-based financing of projects financed by the Academy of Sciences and the GKNT.

Much financing of institutes was replaced with directed funding of specific projects, selected from competing proposals. Projects were to be selected on the basis of recommendations of councils of experts drawn from the Academy of Sciences, the GKNT, and branch industry. In 1988-1989, nearly a third of the resources allocated to institutes in the Academy of Sciences' Department of Informatics, Computer Technology, and Automation (OIVTA) was distributed on a competitive basis [Nemo88; Veli89, 22-23].

- 1989,1990 Decrees on small enterprises.

The ‘‘Statute on the organization of the activity of small enterprises,’’ approved in June, 1989 by the USSR Council of Ministers Commission for the Improvement of the Economic Mechanism, allowed large state organizations to create small enterprises from individual shopes, subdivisions, and separable production units [Krol90, 56]. Many problems, including property ownership, supplies of material and equipment, and hiring practices remained unresolved and establishing small enterprises was difficult. Matters were improved somewhat by the statutes ‘‘On measures for creating and developing small enterprises’’ and ‘‘On the general foundations of the activity of small enterprises,’’ of August 8, 1990 [Ezh9008; Ezh9008b]. Small enterprises in scientific spheres were limited to 100 employees.

The efforts since 1985 to reform Soviet science to a great extent incorporated ideas which were not new. Efforts to decentralize parts of the centralized system of management had been tried to various degrees during the 1960s. The *khozraschet* mechanism had, in various forms, been experimented with for decades. Production and scientific-production associations were products of the 1960s. The program-goal method of planning and the 15- and 20-year Complex programs were continued, most prominently in the Comprehensive Program for Scientific and Technical Progress of the CMEA Countries to the Year 2000 (Program to the year 2000). The introduction of state orders preserved the essential features of centralized directive planning, in spite of its ostensibly being fundamentally an economic mechanism. The previous reform efforts and the discussion surrounding them had produced a considerable pool of ideas and experience on which Gorbachev could draw.

What was new was the extent to which some of these measures were applied, and their combination with a number of measures which had not been tried before. Full *khozraschet* with its emphasis on profit as the primary indicator was implemented to a much greater extent than any time since the New Economic Policy of the early 1920s, extending to Academy of Sciences and VUZ institutes as well as branch institutes and enterprises, and emphasizing the penentration of this mechanism to sub-institute levels.

The measures promoting ‘‘small business’’ also opened the door for much greater decentralization of scientific and economic activity than had been possible before.

The question we seek to answer is how R&D institutes within one particular sector–high performance computing–fared under the various reforms over the years, but under the *perestroika* reforms in particular. Most analyses of Soviet science focus on science as a whole. Issues of technological innovation have been primarily addressed at the aggregate level: the overall level of technology, the number of innovations in the various branches of industry, the economic effect of innovation, etc. Few have investigated individual technologies or specific R&D facilities over time. We seek to examine the results of the reforms mentioned above at these lower level units of analysis. What has changed within the HPC R&D institutes, both in terms of the technical characteristics of R&D projects, the R&D cycles, and the structure of the organizations within which they are carried out? The changes within the Soviet economic, social, and political structures took on a momentum of their own well before the breakup of the Soviet Union which was unanticipated by Gorbachev and his advisors when he assumed leadership of the country, with many negative unintended consequences for the established order. Nevertheless, can we observe in the response of HPC R&D facilities to the reforms the planting of the seeds of a future, more effective R&D system for the Soviet states ?

2.2 Computing in the Soviet Union

The Soviet Union has a long history of research and development in digital computing. The first Soviet digital, stored-program computer, the MESM (Small Electronic Calculating Machine) was built under the leadership of S. A. Lebedev between 1946 and 1951 in Kiev under very difficult, post-war conditions [Khom89; Crow93]. From 1951-1970, at least 60 known computer models were developed in the USSR, although only a third of these were produced with more than 100 units apiece [Davi78, 95; Rudi70]. In 1950 Lebedev moved to Moscow where he continued developing digital computers at the Institute of Precision Mechanics and Computer Technology (ITMVT) [Bard87]. The machines developed here between 1950 and 1965–the BESM, BESM-2, -3, -4, and -6 –were respectable efforts; the BESM-6 in particular was nearly a world-class machine at the time it was built, both in performance and in levels of innovation. Rudins provides a reasonably comprehensive survey of the earliest Soviet machines in [Rudi70].

In 1967 a program to develop a ‘‘Unified System’’ (ES) of upwardly compatible mainframe computers based on IBM’s System/360, /370 mainframes was announced. In the years that followed, a very extensive international computer industry was built as part of large-scale programs to develop the ES mainframes as well as the Small System (SM) series of minicomputers, based on minicomputers developed by Hewlett-Packard and Digital Equipment Corporation [Davi78; Hamm84]. Goodman and other writers have provided surveys of other aspects of Soviet and CMEA computing such as software, microcomputing, networks, high-performance computing systems, and the ‘‘Soviet-style information society’’ [Good79; Stap85; Mche88; Wolc88; Wolc90; Good87; Good88].

In their survey and analysis of the ES program, Davis and Goodman document the achievements and shortcomings of the program, and firmly establish that Soviet computing cannot be properly understood from a technical perspective alone. A proper understanding of the development and impact of computer systems can only be gained by considering economic, political, and social factors as well. McHenry applies a web model to the study of computer-based information systems within Soviet enterprises [Mche85; Mche86]. The web models, discussed by Kling and others in [Klin82], ‘‘view computing developments as complex social objects which are constrained by their context, infrastructure, and history.’’ McHenry’s work and that mentioned above advance the discussion of the development and use of complex technologies under centralized economic regimes based on an ideology of scientific management.

Our work extends existing research on Soviet computing along several fronts. First, it provides an in-depth survey and analysis of Soviet computing within one sector–high-performance computing–which has not been covered adequately in the literature. While the work of authors mentioned above documented the inferior state of Soviet computers widely used in the civilian sector, the possibility remained that HPC was an exception to this pattern. Our work will fill in this missing piece and determine whether or not this was the case, and why. Second, our work further contributes to the discussion of the development of computer technologies under the pre-*perestroika,* directive economic and political system through a more detailed discussion of the R&D process for such machines. Third, our work examines, at the level of technological systems and organizations, the changes occuring within this sector under the *perestroika* reforms. The writings of Goodman, McHenry, and others have described the difficulties encountered by the computing industry in the pre- and early-*perestroika* years. What has been the effect, both direct and indirect, of the changes in the industry’s context and infrastructure?

Fourth, our work represents a significant change in data gathering techniques and abilities. Before *perestroika,* Western researchers had little access to individuals, institutions, and systems in most branches of science, let alone computing. The high-performance computing sector was particularly closed to Westerners. Research was conducted largely on the basis of extensive reviews of published Soviet literature. While such material was rather extensive and useful when properly viewed, it provided a poor picture of the internal operations of research institutions and R&D teams, and provided little discussion of the development process–the design decisions, the tradeoffs, the factors affecting the development and production of a new system. Information on these had to be inferred from reading between the lines, or from limited personal contacts. Under *perestroika,* we have gained unprecedented access to key individuals and institutions and have been able to complement published literature with interviews and direct observation. Such access has both provided a more robust set of data and made it possible to discuss issues which, in the past, could not have been discussed for lack of data.

2.3 Western Literature on Technological Innovation

2.3.1 Technological Paradigms and Trajectories

Joseph Schumpeter is often credited with being the first to identify innovation as the engine of economic development in capitalist economies [Schu34; Schu39]. Since his pioneering work, a large volume of literature has been written about the sources of invention and innovation (large firms, small firms, private inventors), the kinds of organizational and other factors which are associated with successful choice and carrying out of a project, the relationship between state policy and innovation, etc. [Torn83].

Nelson and Winter [Nels77] and subsequently Dosi [Dosi82; Dosi84; Dosi88b] have tried to capture some of the essence of technological innovation and present it in a more unified framework. Their work attempts to account for a certain unpredictability in the direction and rate of technological innovation on the one hand, and, on the other, the fact that invention and innovation do not occur *in vaccuo* but are cumulative activities. Technological innovation is uncertain, but the development of a given technology has a certain orderliness to it in which new developments are built on past achievements.

Nelson and Winter introduce the concept of a ‘‘natural trajectory’’ to describe such a path. ‘‘...[I]t may be that there are certain powerful intra-project heuristics that apply when a technology is advanced in a certain direction, and payoffs from advancing in that direction that exist under a wide range of demand conditions. We call these directions ‘natural trajectories’’’ [Nels77, 56]. According to these authors, progress along a natural trajectory is determined by the dynamic of a ‘‘heuristic search process’’ or research strategy that guides developers in their activities, and of a ‘‘selection environment.’’ A selection environment consists of market and non-market forces that serve to identify the more ‘‘worthwhile’’ innovations [Nels77, 62]. These forces, reflecting the values (not necessarily monetary) of organizations and individuals or non-market features such as regulation and policy, favor certain innovations over others. They communicate powerful signals to the innovators about what development paths are worth pursuing. ‘‘Selection criteria’’ are those criteria by which innovations are judged advantageous or not.

Dosi presents the notion of a ‘‘technological paradigm,’’ which he defines as ‘‘an ‘outlook,’ a set of procedures, a definition of the ‘relevant’ problems and specific knowledge related to their solution’’ [Dosi82, 148; Dosi84, 14]. It includes both the set of exemplars–examples of the objects which are to be developed and improved–and the set of heuristics that specify what the next step should be [Dosi88b]. He defines a ‘‘technological trajectory’’ as ‘‘the direction of advance within a technological paradigm’’ [Dosi82, 148]. Like Nelson and Winter’s natural trajectory, Dosi’s technological trajectory embodies the idea that technologies progress along a path which is neither certain or predetermined, nor random. Nelson and Winter wondered if certain technologies exhibited ‘‘natural’’ paths of development, inherent in the technologies, which would be followed under a wide variety of conditions. Dosi’s technological trajectory, on the other hand, places a greater emphasis on the momentum a technology shows once a technological trajectory has been established.

The notions of technological paradigms and trajectories have received considerable support within the technological innovation research community. Nevertheless, a number of issues remain unresolved, which we would like to investigate in some detail through a study of a number of Soviet high-performance computing projects. There is a basic lack of clarity in the definition and scope of the concept of a ‘paradigm’ which, while making it attractive in the abstract, limits its usefulness in practice. The notion of a technological paradigm has its roots in Thomas Kuhn’s work on scientific paradigms which he used to analyze the nature of scientific progress. His major thesis was that scientific progress is strongly influenced by the nature of the ruling ‘paradigm’ [Kuhn70]. As Clark points out, Kuhn had a difficult time defining unambiguously what a ‘paradigm’ is, but the term has become popular and widely used in the sociology of science [Clar87, 28]. This term, and others similar to it, have been used by Dosi and others in relation to technological change, but with no greater precision.

A more serious issue, perhaps, is the lack of clarity about the scope of usage. In Kuhn’s work it is clear that the term refered to a conceptual framework, a set of heuristics and accepted practice that was predominant throughout a scientific community. As used by Dosi, the term certainly refers to something held by a community or an industrial sector, refering to a category of technology (‘‘automobiles,’’ ‘‘tractors,’’ ‘‘high performance computers,’’ etc.). At the same time, it isn’t clear that the term doesn’t also refer to the ‘‘outlook, the set of procedures, the definition of the ‘relevant’ problems and specific knowledge related to their solution’’ held by individual researchers working on specific projects. Certainly the two levels of application are closely related since a paradigm at the community level reflects the beliefs and practicies of individuals and vice versa. Dosi seems to imply that the regularity observed in technological development–the technological trajectory–, even within individual projects, always occurs within the bounds of some technological paradigm which guides development. But is all such regularity the result of a prevailing paradigm? Here the problems of scope of usage become evident. It is conceivable that regularity in development of a specific technological system over multiple generations does not reflect practice which is standard or accepted throughout the community of those addressing similar issues. In other words, micro-level regularities do not necessarily imply macro-level regularities and the use of a single term either implies that the two are tightly coupled, or that the difference is not significant.

A third unresolved issue is the temporal nature of a paradigm, or how paradigms change over time. Little has been said about patterns of evolution of the paradigms themselves. Assuming the existence of one or more paradigms, what can be said about how one paradigm evolves into another, or how one displaces or is absorbed into another? Under what conditions do multiple paradigms coexist over time?

What is clear, however, is that technological trajectories and paradigms rely to a considerable extent on the beliefs held by those involved in the development of a technology and a host of environmental factors which shape these beliefs and form the ‘‘selection environment’’ which provides strong signals to developers about which developments are possible and beneficial. Beliefs, strategies, and environmental factors are important components of the conceptual framework described in section 2.6.3 which is used as a starting-point for this research.

We use a set of case studies in the Soviet high-performance computing sector to explore these issues and to try to add some more precision to the notions of technological trajectories and paradigms. In particular, we wish to find out if, within the bounds of the existing, imprecise definitions, something which can be called a technological paradigm exists within the high-performance computing sector. Second, we seek to identify the patterns of regularity, the technological trajectories, within Soviet HPC development and understand their causes and the factors which influence them. Third, during a period of considerable change at all levels of Soviet society, are there observable shifts in the paradigms or patterns of regularity?

Within the domain of Soviet computing, the high-performance computing sector provides the best opportunities to explore these issues. Implicit in the work of Nelson and Winter, Dosi, and others is the idea that the shape of a technology is unpredictable and the result of an accumulation of decisions made by individuals directly involved in the development of technology. In the case of the majority of Soviet computers, the model for development–computers from IBM or DEC–was largely imported. The task for engineers was not the development of conceptually new technology, but the imitation of an existing technology. This is an instance in which a technological paradigm, if it can be called that, was directly imposed on an industrial sector, and therefore is not well suited for exploring the dynamics underlying the paradigms themselves. In contrast, Soviet high-performance computers were shaped to a much greater degree by research and development done by Soviet researchers and engineers themselves.

2.3.2 The Innovation Process

The work of Nelson and Winter, Dosi, and others focuses on the patterns of technological change over time but speaks relatively little about how individual acts of innovation take place and the factors–organizational, technical, environmental–which promote it. Other authors have considered such matters at length and have proposed an impressive number of variables which affect the degree to which product innovation takes place within an organization. These have included organizational size, education and skills of innovators, the available pool of theoretical and practical knowledge, degree of centralization of authority, the resources devoted to research and development, and many more [Saha81; Rahm89; Roma90]. Kanter has argued that there are four innovation tasks which take place as an innovation process unfolds and the conditions which promote innovation can be best understood through their impact on these tasks. The tasks are a) idea generation, b) coalition building to garner the support necessary to turn the idea into reality, c) idea implementation, or turning the idea into a prototype, and d) the transfer or diffusion of the innovation into practice [Kant88, 173]. Clearly, these tasks are not carried out in a linear fashion, although there is a rough temporal ordering to them.

In her review of the literature and in her own investigations, Kanter has identified a number of factors which facilitate the tasks mentioned above [Kant88, 173-205]. Factors facilitating idea generation include degree of interaction with demanding customers, cross-disciplinary contact with others inside and outside of one's organization, jobs which are defined broadly rather than narrowly, and organizational expectation of innovation. Crucial to coalition building is the presence of backers and supporters, sponsors and friends in high places. The ability to build a coalition also depends on the patterns of resource allocation within an organization, the nature of coalition relationship, open communication patterns which make it easier for individuals to find partners, etc. Idea implementation is facilitated by a certain amount of isolation from administrative interference and distraction, continuity of personnel, flexibility of organization which permit easily changing plans, and a balance between autonomy and accountability. Transfer and diffusion of a technology is helped by an organization or market which is anticipating the innovation, by individuals who can serve as a bridge between developers and users, and a receptive institutional environment.

The factors identified by Kanter may or may not constitute a complete or primary set and may or may not reflect the factors at work in the Soviet Union or its successor states. As we evaluate the changes that have taken place within R&D facilities of the Soviet high-performance computing sector we will want to be able to draw some conclusions about whether they are proving helpful or not to the innovation process within these organizations. Our case studies will more precisely identify the key factors at work, but evaluating them in terms of Kanter's four tasks will enable use to come to conclusions about their impact.

2.4 Organizational Development

High-performance computers are developed within an organizational context designed, ideally, to facilitate R&D by providing needed financial and material resources, procedures for decision-making, and overall coordination of activities. Historically, Soviet organizations were given little freedom to determine, independently of higher administrative entities, the organizational structure or how resources are to be used. Precise regulations tightly governed the allocation of wages, the types of positions within the organizational structure, the composition of the directorate, the use of revenue received from the state budget or from contract work, the aquisition or sale of capital equipment between organizations, and many other aspects of organizational life and operation. Under the reforms, legislation regarding organizations changed drastically, giving greater freedom to the organizations themselves to determine their own structure and use of organizational resources. An important part of the study of high-perforamnce computing is the manner in which the R&D facilities are changing and the impact of these changes on the HPC projects, or vice versa.

An enormous body of literature has been written about organizations, encompasing an impressive spectrum of perspectives on what the salient characteristics of organizations are. Gareth Morgan provides an excellent overview of some of the major perspectives, which he calls metaphors, which have been used to understand organizations, identifying the origins, strengths, and limitations of each [Morg86]. He discusses organizations as machines, as organisms, as information processing entities, as cultures, and as political systems. Each provides a different although often complementary view of an organization's structure, the role of an organization's environment, and the nature and forces behind organizational change.

It is clear that the environment for Soviet organizations has changed dramatically since 1985. The organizational perspective which places great emphasis on the interaction between an organization and its environment is the organism, or sysems perspective. Here organizations are viewed as a set of interrelated subsystems which rely on exchanges of resources, products, etc. with their environment for sustenance. The organism metaphor has made valuable contributions to the understanding of organizations. It stresses the importance of understanding the relationship between an organization and its environment as well as the relationship between parts within the organization (the organization's structure). Something of a catch-all for anything lying outside the bounds of an organization, environment is a very broad concept treated in many ways in the literature. Individual theories differ on the specifics, but in general the environment plays the following roles:

- The environment is a source of financial resources, material resources, knowledge, qualified people, and technology. In some cases these resources can be generated interally to an organization (e.g. in-house R&D, training), but ultimately if an organization does not draw in resources from its environment, it will lose its ability to function at current levels, to change, and to grow. The environment is also a sink which receives an organization's output.

- The environment is a source of regulation. Explicit regulation through legal structures can affect domains of activity, relationships to other entities in the environment, means of carrying out activities, etc.
- The environment is a source of change and uncertainty. The organism organizational metaphor stresses that change and uncertainty can affect an organization's ability to function and that organizations need to be able to adapt to the environment.

The systems perspective has promoted organizational forms which are more fluid and flexible in structure, better able to adapt to changing conditions and pursue innovative ideas. In its purest form, however, this perspective has weaknesses. It assumes that the environment and an organization can be quantified in a manner which allows concrete measurements of the organization's relationship to its environment to be made. There is also the tendency to downplay the fact that organizational subsystems, unlike biological subsystems, have a will of their own and do not necessary work together to form a ''unified whole'' [Morg86, 71-75]. Nevertheless, this perspective provides a useful starting point for studying Soviet organizations in a rapidly changing context.

Growing out of the perspective of organizations as organisms, or systems, contingency theory refers to the large body of literature directed at the relationship between certain features of the organization's environment, and certain characteristics of the organization itself. In its most basic form, contingency theory postulates that the effectiveness or performance of an organization depends on how well an organization's structure ''fits'' the nature of its environment. Contingency theories originally arose as an alternative to classical organizational theory which postulates that there is an ''ideal'' organizational form. Contingency theories, on the other hand, claim that the ‘‘ideal’’ form of an organization (however that is defined) depends on, or is contingent on, the organization’s environment.

A study by Burns and Stalker [Burn61] is considered an early contingency theory classic. In British and Scottish industrial firms, Burns and Stalker identified two management systems which they labeled mechanistic and organic. In a mechanistic system, corresponding to the machine metaphor, the structure and functions are precisely defined, and exhibit high degrees of functional specialization. In an organic system, however, the structure and functions are much less precisely defined. Burns and Stalker’s conclusion was that mechanistic firms functioned best in stable environmental conditions, while organic firms functioned best when the environment was unstable and changing rapidly or unpredictably. Lawrence and Lorsch extended this research in an examination of the relationship between organizational structure, environment and performance in selected U.S. industries [Lawr67, 151-158; Mile80, 259]. They confirmed parts of the theory established by Burns and Stalker, but added considerable detail to an understanding of what types of organizational structures and processes are best suited to dynamic and complex environments. Other authors have extended the list of organizational elements that must be in alignment to include people and processes [Beer80]; mission, strategy, politics, and culture [Tich83; Smit87; Tosi84]; and technology [Wood65; Perr67] (see [Draz85] for additional references.)

Contingency theories have enjoyed considerable popularity, but support for them in their strongest form has waned. The empirical research has given mixed results. (See [Tosi84] for a review of this research.) There appears to be general support for the idea that organizations and their environments are interdependent, but not strong support for any particular casting of this relationship. Part of the difficulty has been finding useful, broadly applicable definitions for such concepts as ‘‘structure,’’ ‘‘environment,’’ ‘‘performance,’’ ‘‘fit,’’ or other concepts which have been introduced in various contingency theories. Writings such as [Schr80] question some underlying assumptions such as the idea that there is a single best structural ‘answer’ to a specific contextual situation, and that organizations have no influence in shaping their environment. Additional complications arise from the fact that the use of many different units of analysis make cross study comparisons difficult.

Several authors have investigated the relationship between organizations’ structure and the technologies they develop. Scott provides a review of this category of contingency theory [Scot90]. Much of the work has been devoted to testing postulates such as:

- the greater the complexity of the technology developed within an organization, the greater the organization’s structural complexity in terms of differentiation of function, level or location;
- the greater the certainty about what problems or procedures are to be encountered the lower the formalization and centralization of decision-making;
- the greater the extent to which the items and elements involved or the work processes are interrelated, the more resources must be devoted to coordination mechanisms.

He concludes that [Scot90, 117]:

> given the many types of problems cited (multiple conceptions, variables, indicators, samples), the results of empirical studies conducted up to the present provide evidence for linkages among technology and organizational structure. The evidence is reasonably consistent but not particularly strong.

Scott proposes a number of measures to improve the arguments and strengthen the evidence for contingency theories. These include narrowing the focus to the portions of an organization which is concerned with a single, or dominant technology; examining a looser coupling of structure and technology which does not imply a single, deterministic relationship but allow for the possibility of multiple suitable structure-technology relationships; and recognizing that organizations are affected by many factors in their environment (''wider rules and regulations, belief systems, and legal frameworks that surround, support, and constrain organizational forms'') which operate to reduce or constrain technological effects. Scott also recommends an increased temporal emphasis, noting that the relationship between structure and technology is not static, but is better viewed as an interdependence evolving over time.

There are a number of implications for the study of Soviet high-performance computers and their associated R&D facilities. First, Western writing on contingency theories for the most part is based on an assumption that until recently did not hold in the Soviet Union–that individuals and groups within an organization have the authority to modify the organization's structure. Prior to *perestroika,* principal decisions about the structure of an organization such as an enterprise, a factory, or a research institute were made, or at least authorized, outside of the organization. Proposals for the creation of an organization or the modification of its structure and function had to be approved at higher levels within the ministry, or the Academy of Sciences, often at the level of the Council of Ministers. The formal structure of a given category of organization, such as research institutes, was very similar throughout the Soviet Union. This can be viewed as an extreme case of environmental influence on the structure of the organization, but this degree of determinism is not supposed by even the most ardent contingency theory determinists in the West.

One of the changes under *perestroika* has been the greater delegation of decisions regarding organizational structure to the organizations themselves. The influence of (certain components of) the environment has become less direct. The Soviet condition to a greater degree satisfied a basic assumption of contingency theories. It has therefore become more appropriate to investigate the environment-organization relationships of Soviet R&D facilities since 1985 in light of some of the research on contingency theory in the West.

Given the lack of a clear and unified set of results in the Western contingency theory literature, a second implication for the study of Soviet high-performance computer R&D facilities is that a narrow investigation of linkages between a small, preselected set of variables would probably be misguided. Following some of Scott’s recomendations, we focus our study on divisions within R&D facilities where a single technology is dominant. We will also examine the technologies and organizational structures within a broad context, recognizing that the relationships between technologies, organizational structure, and the organizational environment can be loosely coupled and evolving over time, and that there can be a multitude of factors which influence them simultaneously.
While in this study we have selected a limited number of dependent variables–high-performance computing systems and the structure of their R&D facilities–we leave the set of independent variables rather loosely bounded and defined.

2.5 Research Questions

To address the issues raised thus far, we focus on four primary research questions:

- How have high-performance computing systems developed within the Soviet Union and since its breakup? Which factors best explain the direction and nature of their evolution?

- How have Soviet high-performance computing research and development facilities and the computing systems they developed changed since the start of the *perestroika* reforms in 1985? We will not limit ourselves to direct effects of the reforms, since changes in laws and policy have secondary or tertiary effects which can be as important as those originally intended. The study will examine the evolution of HPC technologies, changes within HPC R&D organizations, and contributing factors in the broader political, technical, social, and economic environments as they influence developments within the HPC sector.

- What conclusions can be drawn about the nature of Soviet R&D, Soviet ability to develop and produce advanced technologies, and the viability of HPC R&D in the domestic and international context? Is there evidence that the changes are laying a foundation for more effective R&D and greater contribution and participation in global developments in science and technology in the future?
- How well do Western theories and models about technological change and organizational development help us understand the changes in progress in Soviet high-performance computing? What are the strengths/weaknesses of the theories and models in the context of Soviet HPC? In what ways must they be modified to explain changes in this sector properly?

2.6 Research Methodology

In this section we outline the multiple case study with embedded units of analysis methodology used to seek answers to the questions presented in section 2.5. In addition to specifying the units of analysis and constituent cases, we discuss the case study methodology in light of the theoretical perspective which we feel should be used in this study. As we will explain, theories can differ not only in their content–the specific variables used and the manner in which they are related–but also in their assumptions about what

Markus and Robey [Mark88] term the causal structure, or the fundamental assumptions about the nature and direction of causality a theoretical framework claims to represent. It is important that the methodology be well adapted to the causal structure of the theoretical perspective.

2.6.1 Units of Analysis

We will focus on change in two areas: computing systems developed within Soviet high-performance computing R&D facilities and the structure of these facilities.

The hardware and software systems developed at Soviet R&D facilities represent the end result of an intricate interplay between technological, economic, social and political factors. While this interplay is quite complex, we are interested in the factors which play the most significant roles in influencing the nature of the final outcome, the computing system. We analyze the physical, logical, performance, and, to the degree possible, operational characteristics of specific systems, identifying how these characteristics have changed over time in either the same models or a succession of different models.

As researchers like Dosi have pointed out, technology is more than simply physical artifacts. Dosi defines technology as ‘‘a set of pieces of knowledge, both directly ‘practical’ (related to concrete problems and devices) and ‘theoretical’ (but practically applicable although not necessarily already applied), know-how, methods, procedures, experiences of successes and failures and also, of course, physical devices and equipment...’’ [Dosi82, 151]. In our study of Soviet HPC, we will consider the non-physical parts of technology, but only to the degree that they are reflected in the physical. We will focus on the physical systems and the construction, designs, and architectures, the means of development and manufacturing, the underlying concepts and design principles, and the knowledge embedded in them rather than abstract knowledge possessed by a developer but not necessarily applied.

Our second unit of analysis is the structure of R&D facilities within the Soviet high-performance computing sector. As has been discussed, there are many different perspectives on what an organization is, and what constitutes its structure. The organizational unit we are most concerned with is the division. An institute may have many divisions carrying out many kinds of research in many fields, some HPC and others not. Within a division, however, work generally is unified around a single product, or family of closely related products. We agree with Scott that [Scot90, 119]:

> [t]he difficulty [in analyzing the relationship between technology and organizational structure], of course, is that such averaging approaches ignore the realities of both technological diversity and structural differentiation–the coexistence within organizations of subunits with varying technologies and structures. For this reason, it is my belief that technology-structure arguments are best suited to the subgroup (for example, departmental) level. Most departmental units can be characterized as containing one or a least a dominant technology.

Hage also supports this perspective. In his view, an organization is oriented around a rather specific set of processes, knowledge, and technologies [Hage80, 10]. In his definition, large companies might consist of separate organizations–divisions–which produce product lines on a rather autonomous basis. Such divisions often differ in the processes they use, the knowledge they apply, and the technologies they utilize. They deserve to be examined separately.

Although organizational structure has been defined and measured in many ways in the literature, there is, as Ford and Slocum point out, some agreement that three principal dimensions are complexity, formalization, and centralization [Ford77, 562]. Complexity refers to the extent of differentiation in a system, be it vertical (the number of hierarchical levels), horizontal (the number of functions, departments or jobs), or geographic. Formalization refers to the extent to which rules and procedures are specified and/or adhered to. Centralization is defined as the locus of formal or informal control within a system. A fourth dimention, prevalent but not as widespread, is administrative intensity which refers to the size of the administrative component relative to the direct labor component.

2.6.2 Rationale for Using the Case Study Methodology

We employ a multiple-case case study with embedded units of analysis. Case studies are appropriate for studying ‘‘how’’ questions focusing on contemporary events in which researchers have no control over the research variables [Yin89]. We are interested in the manner in which computer systems and R&D facilities within the high-performance computing sector have changed, rather than in a quantitative assessment of such change. Case studies are also appropriate when the number of variables is large, and their relationship to each other is complex and/or poorly understood. We focus on a number of variables which we feel have the greatest explanatory power, but other variables which emerge as significant during the investigation will also be taken into account.

The case study is appropriate given the nature of the theoretical structure which should be used for this kind of study. Markus and Robey have written an insightful article on causal structure in theory and research [Mark88]. While their article specifically focuses on theories about the relationship between information technologies used in organizations and organizational structure (we focus on technologies which are created rather than used in organizations), their argument is applicable to our study.

Rather than analyze theories in terms of their content, Markus and Robey examine theories in terms of their structures–the theorists’ assumptions about the nature and direction of causal influence. Specifically, they examine three dimensions of causal structure: causal agency, logical structure, and level of analysis.

They argue that there are three conceptions of causal agency (defined as the analyst's beliefs about the identity of the causal agent, the nature of causal action and the direction of causal influence among the elements in a theory) which they term the technological imperative, the organizational imperative, and the emergent perspective [Mark88, 585-589]. In the technological imperative perspective, information technology is viewed as a cause of organizational change; in the organizational imperative perspective, information technology is a dependent variable and a great deal of choice, control and ability to select information technologies and shape organizational structure is assumed on the part of individuals within the organization. In the emergent perspective, organizational change emerges through the interaction between the information technologies and users in a manner which is not very predictable. In other words, there are no clear and simple causal relationships.

The emergent perspective is most appropriate in our study for several reasons. Redirecting Markus and Robey's focus on information technology as a tool used within an organization to information technology as a product created within an organization, we would interpret the technological imperative as claiming that the nature of the technology being developed determines organizational structure and the organizational imperative as giving entities within an organization great freedom in determing the direction of technology development. There are several reasons why these perspectives are too limiting for our study. The technological imperative assumes a high level of rationality on the part of decision-makers throughout the organization, that their decisions are based on objective analyses of the characteristics of the technology and the organizational structures best suited for its development. It leaves little room for decisions based on factors other than the tools' objective characteristics, such as any social meaning the technology may embody, or factors external to the organization which influence development. The organizational imperative gives decision-makers considerable degrees of freedom to determine the course of development without placing much emphasis on constraints inherent in the technology, and environmental factors beyond the control of decision makers which enable or constrain development.

In general, but especially during a time of rapid change in the Soviet political, economic, and social arenas, the likelihood is high that the development of technology and changes within organizational structure are best described not by simple, unidirectional causal relationships, but by a complex interplay of many factors. The emergent perspective best enables us to capture this complexity. The case study, with its attention to the richness and complexity of actual situations is well suited to investigations from the emergent perspective.

A second dimension of causal structure is logical structure, the logical formulation of the theoretical argument. Markus and Robey, following other researchers, distinguish between variance and process theories. Variance theories are generally rather static in nature, seeking to predict levels of dependent variables from the values of independent variables. In other words, they assume that the outcome will invariably occur when necessary and sufficient conditions are present. As stated in [Mark88, 590], ‘‘If X, then Y; If more X; then more Y.’’ In contrast, process theories hold that certain conditions may be necessary for an outcome to occur, but their presence does not necessarily imply that the outcome will occur.

A knowledge of process is of great importance. Quoting L. B. Mohr, Markus and Robey state that ‘‘necessary conditions can comprise a satisfactory causal explanation when they are combined in a ‘recipe that strings them together in such a way as to tell the story of how [the outcome] occurs whenever it does occur’’’ [Mark88, 590]. In his study of organizational metaphors, Morgan also proposes ‘‘the most effective story line’’ as an analysis tool well suited to capturing the richness of change over time [Morg86, 329-337]. This strategy allows us to draw on multiple perspectives on organizations and technology to find the best explanations for observed events and situations, and link these insights together into an integrated picture which not only describes what has transpired and why, but can provide a foundation for prescriptive or prognostic analyses of what some possible avenues of change are, or how matters may advance in the future.

A knowledge of the temporal relationships between elements in a setting is crucial to understanding final outcomes. Process theories have the advantage of greater empirical fidelity, albeit at the cost, potentially, of generalizability. Markus and Robey are careful to point out that they do not give up all claims to generalizability, however: ‘‘By accepting a more limited definition of prediction, one in which the analyst is able to say only that the outcome is likely (but not certain) under some conditions and unlikely under others, process theorists may be able to accumulate and consolidate findings about the relationship between information technology and organizational change’’ [Mark88, 593].

The temporal component is crucial to our study. In seeking to accurately describe the processes and consequences of change in a wide range of factors in Soviet high-performance R&D facilities and technologies, it is crucial to investigate how the factors change and interact over time. Reform in the Soviet Union consists not of an isolated event but of a series of changes in political, legal, social, economic, technological spheres that build on each other over time. While it is theoretically possible to study this phenomenon using variance theories, such an approach is likely to miss a great deal of the richness of change and give results which, while ostensibly more generalizable, reflect actual circumstances only weakly.

The case study is an appropriate methodology for use with process theories. It captures the richness of the process of change and enables, indeed encourages, a longitudinal

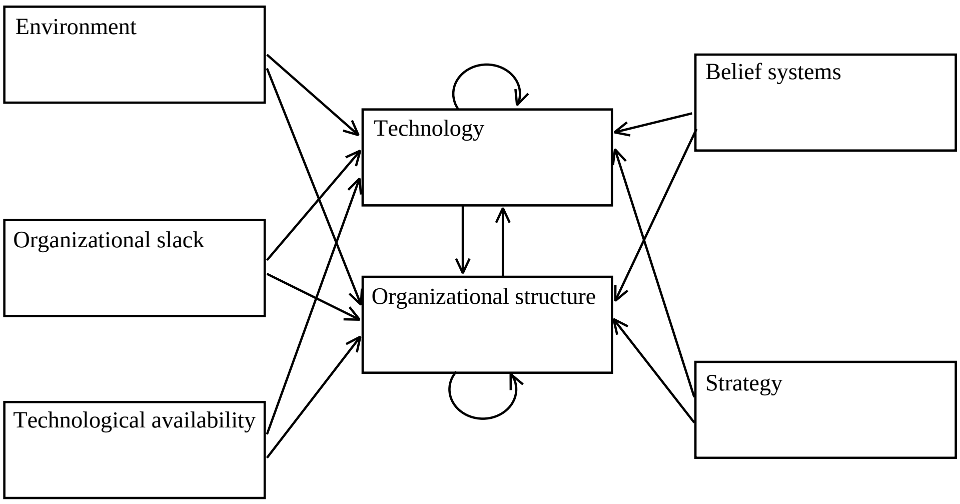

Figure 2-1 Conceptual Framework

approach, tracing change and its impact over time. It permits the capture of the dynamics of the interplay between factors as they evolve and change, something difficult to do using other methodologies.

2.6.3 Conceptual Framework

The conceptual framework shown in figure 2-1 seeks to integrate the most salient factors, or groups of factors, influencing the development of Soviet high-performance computing systems and their associated R&D facilities. It recognizes the considerable overlap between the factors that play a role in both organizational and technological development. Many of the elements in this framework have already been discussed. Here we reiterate some of this discussion, and discuss the remaining factors and some features of the framework as a whole.

2.6.3.1 Technology and Organizational Structure

The two units of analysis, the technological system and organizational structure, have been discussed in section 2.6.1. One characteristic which they share is momentum. In other words, their future state is strongly influenced by the current state. Once established, organizational structures can be difficult to change. When they do change, it is rare that they change drastically in one step. Rather, they evolve so that the structure tomorrow represents an incremental change in today's structure. Because it is generally more difficult and more expensive in terms of time, money, and energy to change a structure drastically, today's structure puts practical constraints on how much a structure can be changed, and how quickly.

A characteristic of technological change pointed out by [Nels77; Dosi82; Saha81b; Saha85] and others is that most technological innovations exhibit an incremental nature. Today's technology is generally an extention of yesterday's, rather than a radical departure. Gradual improvement is a dominant characteristic. A significant amount of innovation and improvement originates through 'learning-by-doing' and 'learning-by-using' [Saha85; Dosi88b]. Dosi also points out that it is well established that

> 1) in spite of significant variations with regard to specific innovations, it seems that the directions of technical change are often defined by the state-of-the-art of the technologies already in use; 2) quite often, it is the nature of the technologies themselves that determines the range within which products and processes can adjust to changing economic conditions; 3) it is generally the case that the probability of making technological advances in firms, organizations, and often countries is, among other things, a function of the technological levels already achieved by them [Dosi88b, 223].

Thus the technology which exists today has a considerable impact on the technology developed tomorrow, both suggesting and constraining new avenues of development. For example, the need to maintain software compatibility from one computer generation to another constrains the path of hardware development. As engineers work on a particular design, their knowledge about a particular approach increases. They are more likely to pursue development paths which build on their expertise than move in directions in which they have limited knowledge.

High-performance computing systems demonstrate another way in which a technology influences the future development of the same technology. Computer-aided design and simulation systems running on current computer models are often used to develop the next generation systems. The complexity or thoroughness of the modeling depends on the capabilities of the software systems and the hardware on which they run.

2.6.3.2 Environment

The importance of the environment–that which lies outside the boundaries of an organization has been identified as important in both the technological innovation and organizational development literatures. It provides many of the resources and signals to developers which constitute the ‘‘selection criteria’’ shaping researchers’ decision-making. The construction of advanced technologies and an organization’s vitality depend on its ability to acquire the financial, material, and political support necessary to carry out its activities over the long term. As we have seen, studies on innovation in the Soviet Union and on Soviet computing have also placed emphasis on the role of the context within which innovations take place. The projects which we are studying all have a strong applied nature; the development goals include the construction of physical machines which are oriented to one degree or another to use beyond the boundaries of the R&D facility.

In our case study we view the environment not as a single entity which can be represented by a single metric or label, but as a set of factors, each having its own influence on our units of analysis. These include, but are not limited to, project sponsors and funding organizations, customers, upstream suppliers, series production factories, the nature of the Soviet economic system (the economic macrostructure), legislation, and foreign export control policies. Two components of our conceptual framework, technological availability and organizational slack, contain elements which could easily be considered part of the environment. We single them out because of their importance to our understanding of developments in Soviet HPC and because they are not confined to the world external to an organization.

2.6.3.3 Technological Availability

Technological availability refers to the presence and accessibility of technology needed to carry out some desired line of development. Technology here refers to physical artifacts such as components, tools, and examples of promising developments (called technological guideposts by Sahal [Saha85]), processes, and technical know-how. The presence or absence of key technologies has a strong, direct impact on other technologies, impacting the perceptions of what is feasible, the development timetable, and the quality and characteristics of the final product.

Although the availability of specific technologies is not usually a sufficient condition for the development of a particular high-performance computer, it is often a necessary one. The lack of certain technologies forces efforts to compensate through design modification, the development of substitute technologies, or greater efforts to acquire technology by other means. Such efforts have strong impacts on the nature of the end product and the time needed to develop it.

Aspects of technological availability which have implications for organizational structure are the presence of know-how and examples of successful organizational structures. While in general certain types of technologies (i.e. telecommunications) can support certain organizational structures (i.e. geographically distributed), in our study know-how and examples of success play a more significant role. Organizational leadership may choose to pursue a particular form of change based on their own experience, or examples of changes which they observe in other organizations.

2.6.3.4 Organizational Slack

Organizational slack refers to the amount of resources available to an organization [Meye82]. It can include financial and material resources, knowledge, people, or even items of barter value such as bricks. Clearly these resources are necessary to sustain the activities of an organization. The degree to which these resources are slack–available in quantities exceeding that needed for the organization to maintain is core activities–plays an important role when organizations undergo change. While an abundance of resources can allow an organization to ignore or respond slowly to problems, transformation can be greatly hindered when there is a lack [Hage80, 274-276]. Efforts such as retooling may not be carried out when there are inadequate resources constraining the options for change.

Organizational slack does not refer solely to resources contained within the organization. An organization may have a considerable in-house reserves of capital, equipment, and know-how. Its ability to go outside and acquire such elements as lines of credit or ready supplies of inputs is also part of its slack.

Two important components of organizational slack are the quantity of resources available, and the degree of discretion which individuals within an organization have over them. Both components have changed significantly in the Soviet Union in recent years. Reforms in legislation have given individuals within organizations throughout the economy much greater freedom to manage their own finances, to make decisions about how finances are to be allocated, and resources accumulated. Changes in the quantity of resources available is a secondary effect of *perestroika* resulting from a number of factors including changing accounting practices, inflation, decreases in the military budget, and the general poor state of the economy.

2.6.3.5 Belief Systems

The theory of technological paradigms places great importance on the set of beliefs about ‘‘the problems that must be tackled, the tasks to be fulfilled, a pattern of inquiry, the material technology to be used, and the types of basic artifacts to be developed and improved’’ [Dosi88]. Individual projects are strongly driven by design philosophies which govern how design objectives are to be prioritized and met, and how tradeoffs are to be resolved. Changes in key components of a design philosophy can result in significant shifts in project design and construction. Under conditions of such dramatic change such as in the Soviet states, it would not be surprising to observe changes in the philosophies behind HPC development, which would manifest themselves in changes to the technologies.

Belief systems play an important role in the organizational development literature as well, particularly in regard to organizational transformation. The cultural metaphor in particular emphasises on the role of the ‘‘world-view’’ of individuals and groups within an organization, but the organization as a system metaphor also recognizes the role of the beliefs of key decision-makers shaping strategy and directing decisions about the organization’s structure, domain of activity, mission, etc. [Gree88; Hini88]. It is also possible, although by no means certain, that a changing environment can result in a shift in basic beliefs about an organization’s appropriate sphere of activity and principles of organizing, paving the way for alterations in both R&D programs and structure.

2.6.3.6 Strategy

In a study like ours, which emphasises the temporal aspects of technological and organizational development, strategy is a one element which helps us understand the courses of action taken by individuals or groups of individuals. It is a vehicle by which elements of a belief system are translated into concrete changes to technology or organizations, opportunities and constraints of the environment are reflected in the characteristics of the HPC system or the organization.

The word strategy is used in a number of different senses in the literature and, as Chaffee points out, often with little concensus. Mintzberg has isolated five definitions: strategy as a plan, pattern, position, perspective, and ploy [Mint88, 13-30]. As a plan, strategy is viewed as a preconceived course of action. Within the organization as a system perspective, strategy is more likely to be viewed as a pattern which emerges through the actions of individuals or organizations. In constrast to strategy as a plan, which focuses on intent, this definition examines actions which actually occur. As a position, strategy reflects the selection of a particular domain, or niche within an environment. As a perspective, strategy is a way of perceiving the world and one’s place in it rather than a chosen position or action. It is integrally linked with belief systems. Most often found within political metaphors, strategy as a ploy involves the creation of a diversion, in order to attain other, higher-level goals.

These views of strategy can complement each other. Each highlights different elements which help us understand an organization’s course of action and the path along which its technology develops. Most relevant to our study are strategy as a plan (intended strategy) and a pattern (realized strategy). Together, they help us understand what courses of action were intended, and which actually occured. A comparison of these can yield useful insights into the reality of technological development in the Soviet context.

Strategy as a ploy does not play a large role in our case studies. The two other types of strategy–strategy as a perspective and as a position–are, to a degree, incorporated under the heading of ‘‘belief systems.’’ They both reflect a deeper understanding of the nature of the organization, its role, and the appropriate way of conducting its business.

2.6.4 Constituent Cases

Our study is limited to HPC projects which resulted in the construction of at least a prototype and their successors. We do not discuss the dozens of projects which progressed no further than paper design or abstract theoretical conceptions. The latter are too numerous to be considered in depth, contribute little to our understanding of the development of advanced technologies within the broader socio-economic context, and have had little or no impact on the computing needs of the country.

Because the Soviet HPC sector consists of a modest number of projects, organizations, and individuals, we are able to discuss nearly all R&D facilities and projects which satisfy the above criterion. The core of the study will be in-depth case studies of selected lines of development at three R&D facilities complemented with a less thorough treatment of approximately a dozen others. The core studies will examine developments at the following institutes. The computer systems of interest developed at each are listed in hard brackets:

1. Institute of Precision Mechanics and Computer Technology (ITMVT), Moscow [El’brus family]
2. Scientific Research Institute of Control Computing Machines (NIIUVM), part of the Impul’s Scientific Production Association, Severodonetsk [PS-2x00]

3. Computer Center of the Siberian Department of the USSR Academy of Sciences (VTs SO AN SSSR)/Institute of Informatics Systems (ISI) Novosibirsk [MARS-M, MARS-T]

These organizations and their projects form a cross-section of the sector as a whole, and are useful for illustrating the key features of Soviet HPC R&D. They constitute two industrial R&D facilities (with ITMVT having dual subordination to the Ministry of the Radio Industry (Minradioprom) and the Academy of Sciences), and one purely academic facility (VTs SO AN SSSR/ISI). The computer systems developed within them reflect both applied industrial and academic research orientations. The El'brus and PS-2x00 are the two most successful families of Soviet HPC computers in the sense of numbers of units manufactured, and the El'brus line includes the most powerful to reach series production. ITMVT is the leading HPC R&D facility in the country. The machines include both those which push the boundaries of the capabilities of Soviet industry, and those which stay comfortably within its boundaries. These organizations are geographically distributed, lying in Moscow, the Ukraine, and central Siberia,.placing them at various distances, both physically and metaphorically, from the center of power. The organizations range in size, from tens to thousands of workers. Levels and percentages of support which come from the state budget vary significantly. The projects reflect a wide range of research approaches, from architectures reasonably well-researched in the West to radical, unproven experimental designs. The user communities range from non-existent to large (hundreds or thousands of users). In short, factors and trends which affect other organizations on Soviet HPC are likely to impact one or more of these. Such diversity within one sector enables us to observe changes under a variety of conditions, laying a rich foundation for analysis.

Besides those covered in our study, there are undoubtedly secret military projects which we know nothing about. Their absence will not invalidate the conclusions of the study. First, many of the systems discussed in our study were designed primarily for the military sector. By definition, our study leads to some conclusions about computers used in the military. Second, highly secret projects have a direct impact on only small portions of the military. They have little impact on the overall state of Soviet high-performance computing. To have a broader impact they must, necessarily, be publicized and made more generally accessible. Similarly, research results coming from such projects will have a broad impact only if they are incorporated into systems which gain greater visibility and use.

2.7 Data Sources and Collection, Analysis, and Validation

2.7.1 Sources

Much of the detailed information about the HPC systems is found in printed matter: books, open journals, and institute publications. The Mosaic Group at the University of Arizona has gathered such information for many years. While we have obtained much of this material through Soviet publication bookstores and direct subscriptions, some of the most informative material has been given to us during visits to Soviet institutes.

We also rely heavily on conversations with individuals intimately familiar with the HPC projects and institutes. They not only have provided technical information not available through publications, but also are the best sources of information on questions regarding organizational change, technological developments, and the broader development context. We have conducted on the order of a hundred semi-structure and open-ended interviews with individuals who work in, or are knowledgable about, these organizations and their projects.

We have made visited nearly all of the R&D facilities mentioned in our study and had multiple site visits to the institutes in our core studies over a period of several years. In each case we have been able to evaluate directly the state of the technology and the organization at regular intervals since 1989, and have been able to gather detailed information from sources in prior years. Multiple visits provide a set of longitudinal data tracking developments over time. Thanks to electronic mail, on-going communication with many individuals in this sector has become practical.

2.7.2 Analysis

The study analyzes multiple cases and embedded units of analysis. Each case and each unit of analysis must be examined individually, and as a part of a larger whole. In each case, we will seek to develop the ‘‘most effective story line’’ to understand what happened and why. For each project we will identify the principal factors shaping development of the technology and its organizational context. In chapter 8, we will provide a cross-cutting analysis of the individual cases, identifying similarities and differences between the individual cases and coming to broader conclusions about Soviet ability to conduct R&D in advanced technologies, technological innovation, and organizational development.

2.7.3 Validation

To the degree possible, we obtain multiple sources for data items. This includes confirming data using multiple written and oral sources, as well as using the same or different sources at multiple points in time. In the past, this method has not always ensured the validity of the data. Official sources were widely parroted. Under *perestroika*, however, individuals have been much more willing and able to speak freely. We have even had occasion to test real machines to get ‘‘live’’ performance data [Wolc91]. Finally, the core cases have been reviewed by individuals who actively participated in the projects discussed. Other chapters also have been reviewed by individuals more broadly familiarity with Soviet HPC.