

Report of the 2020 Commission on Science and Technology

INTRODUCTION: Science and Engineering at the University of Virginia

Unprecedented advances in science, technology and engineering offer new opportunities to lengthen life, spur economic growth, revolutionize manufacturing and business, shape democratic processes, protect the environment, strengthen national defense and generally improve our daily existence.

This knowledge explosion and its impact on society and culture pose challenges and opportunities for every college and university. Progress in mathematics, natural sciences, engineering, and medicine originates -- directly or indirectly -- in the scholarship of universities where most fundamental long-term research occurs.

This progress depends strongly on the education of our future scientists and engineers. It also requires sound scientific and technological literacy. All citizens, legislators, jurors and voters will need to judiciously evaluate how society will use these many advances.

New questions will face political scientists, bioethicists and business managers. Artists, literary scholars, historians and architects will gain new tools. Scientific and technological advances now influence education and research in every subject taught at every university. In earlier times, "educated" people needed only a knowledge of history and literature. Now a person is not considered educated unless he or she also is literate in science and technology.

Thus, it is appropriate to ask whether the University of Virginia has fulfilled its research and education missions in science and engineering as befits a leading public university. The answer is, quite frankly, **no**.

UVa's reputation as a premier public research university is based primarily on its excellence in humanities and professional programs in law and business. The university's science and engineering programs are not so well regarded. According to rankings in the August 2000 issue of *U.S. News & World Report*, UVa tied for first place with the University of California at Berkeley among public universities. Its graduate engineering programs, however, are ranked 36th, substantially lower than other top-10 public institutions. The situation in medicine is similar: UVa is ranked 30th, far below all but one other university in the top 10.

A 1995 National Research Council publication also confirmed these rankings for UVa's graduate programs. The University of California-Berkeley had 35 disciplines ranked in the top 10, including seven in engineering, seven in the physical sciences and seven in the social and behavioral sciences. UVa had none in any of these three categories. Five disciplines, however, were ranked in the top 10 -- four in the humanities and one in biological sciences -- while UC-Berkeley had 14 -- 10 in the humanities and four in the biological sciences.¹

For a premier research university, the contrast between the humanities rankings and those in science and engineering is surprising and disappointing. The predominate reason is the meager support for science and engineering. Despite this, UVa's science and engineering faculty has compiled outstanding teaching and research records.²

U.S. News & World Report ranks UVa's graduate biomedical engineering program 15th in the nation, its graduate psychology program 16th, and its graduate materials science program 21st. Some departments are competitive in winning federal grants for research. On a funding-per-faculty basis, the chemistry faculty ranks 12th in the nation in federal funding, while microbiology ranks seventh in grants from the National Institutes of Health.

The University has achieved these successes in the face of great obstacles. Historically, UVa's science and engineering programs have been small, by both internal and external comparisons. Measures of excellence in universities reveal a high correlation between department size and quality. Undersized departments, unable to offer the range of courses required by the best graduate students, lack the breadth needed to keep up with the expansion of knowledge.

The National Research Council figures also show that in the College of Arts and Sciences, humanities faculty numbers are 2 percent higher than average, compared to the top-20 NRC-ranked departments. Meanwhile in the sciences, faculty size is 34 percent less. Although UVa has many outstanding individual scientists, the University as a whole falls short of the critical mass needed to be among the leading institutions. The large number of unfilled faculty lines in the College and in the engineering school aggravates this situation, as positions remain unoccupied because of insufficient funds to start up new faculty laboratories.

Space is another constraint. UVa does not have adequate room for its existing faculty to conduct first-class research programs, and it also lacks space for additional faculty. National agencies repeated cite UVa's lack of space as a key reason why they cannot fund research at requested levels.

¹University ranking data are discussed at greater length in Appendix A, available on the commission's Website, <http://www.virginia.edu/virginia2020/science/science-docs1.htm>.

²Appendix B, also on the Website, describes many of the excellent programs in education and research in the College of Arts & Sciences, the School of Engineering and Applied Sciences and the School of Medicine.

The University today is a public institution with a national presence. Its faculty and alumni occupy positions of leadership and responsibility in science and engineering organizations across the nation and play a prominent role in formulating national policy in a multitude of fields. UVa has an obligation to the nation and to the Commonwealth of Virginia to advance research, to educate its students to conduct this research, to educate young people to understand science and technology, and to advance economic development.

This has always been the University's mission. Thomas Jefferson believed that social and economic progress rested, in part, on advances in science and technology. This University initially distinguished itself among its peers by emphasizing the "useful sciences." Achieving Jefferson's vision for the entire University now depends significantly on the quality of its science and engineering programs, both in teaching and in research. The ability to create programs competitive with those at the best universities in the nation will only sustain and enhance the University's stature.

Essentials for Advancing Science and Engineering

The 2020 Commission on Science and Technology believes that any initiative to attain excellence in science and engineering should be based on the following seven principles:

- 1. The advancement of knowledge in science and engineering increasingly requires the collaboration of individuals and groups that span disciplines.** While multidisciplinary collaborations have become an increasingly productive and significant source of disciplinary strength, the University has a classic organization of schools, each containing disciplinary departments. Encouraging multi-disciplinary efforts will promote insightful discovery and invention and will require creative thinking about the organizational and physical structures that can best foster them.
- 2. The quality of the individuals involved and their sufficient number are critical to the success of any endeavor.** Besides attracting the most talented undergraduate and graduate students, UVa must place a priority on recruiting, retaining and nurturing world-class scholars, teachers and administrators capable of attracting colleagues of similar caliber. In many areas, the University must add high-quality faculty, since the small size of many departments in science, engineering, and medicine precludes achieving excellence.
- 3. Excellent research and educational programs require appropriate research laboratory space, equipment, and teaching facilities.** Fully functioning laboratories and equipment also require adequate technical support staff. The current lack of sufficient and properly equipped and staffed space for research in

science and engineering undermines the University's efforts to recruit and retain faculty, to attract externally sponsored funding, and to conduct research.

4. **The University must target a select group of science and engineering areas for world-class excellence while providing strategic, persistent advancement and evolution of existing programs as opportunities arise.** Since achieving excellence in all fields simultaneously simply is unaffordable, the University must make careful choices. UVa will need to assess intrinsic intellectual merit, examine the strengths and weaknesses of existing programs, identify potential synergies, evaluate where new knowledge can be most readily positioned, and carefully consider available and potential funding. The University must be practical as well as visionary. It also must periodically reevaluate current areas and make new choices to keep abreast of the rapid pace of change in science and technology.
5. **The University should select focused initiatives to bolster science and engineering so to broadly and fundamentally advance disciplines across the University.** Initiatives should build on the strength of existing faculty and their research. Resources for targeted areas of excellence must not be reallocated from productive existing programs. On the contrary, the University should seek new resources to build the infrastructure, the faculty, the student populations and the education programs on disciplinary fronts where advancement is likely.
6. **Excellence in research alone is necessary but not sufficient to ensure excellence in education.** Researchers must have the incentives and resources to deliver the results of their work to the classroom so that students receive the best current understanding of their field, not yesterday's wisdom.
7. **Programs should advance the wellbeing of the residents of the Commonwealth and the nation while promoting appropriate, vigorous and prudent economic development.** Science and technology are the basis of much of the economic growth in the Commonwealth and the nation. The University needs to exploit opportunities to apply its research results and to ensure that all students are technologically literate and equipped to participate in the new technology-based economy. The University also must consider the impact of its choices on the immediate Charlottesville area, emphasizing sustainable use of local resources and respecting the character and culture of the region.

THE RECOMMENDATIONS

Taken together, this commission's recommendations provide an ambitious plan to attain world-class science and engineering programs at the University of Virginia. The strategy is twofold.

The commission proposes creating **three high-priority "focus areas"** where the University already possesses a competitive advantage:

1. **University-wide information initiative**
2. **Initiative in quantum and nanoscale science and engineering**
3. **Initiative for the study of biodifferentiation**

Coordinating activity in these three focus areas and applying new resources will allow rapid deployment of new and innovative programs in teaching and research, raising the standing of science and engineering at the University and jump-starting the advancement process across the sciences and engineering.

Complementing these three initiatives, the commission also recommends targeting some systemic barriers to excellence that now hamper advances in the sciences and engineering. The University should act immediately on these **four long-term recommendations** as a complementary strategy to promote long-term overall excellence:

4. **Make key strategic faculty appointments supported by an associated investment in the renovation and equipping of their laboratories.**
5. **Recruit and support the nation's best graduate students.** This is critical to the long-term vitality of all of our science and engineering programs and will directly affect the success of undergraduate education as well as on the effectiveness of our research enterprise.
6. **Create a "fund for excellence in science and technology" to nurture innovative new research activities.**
7. **Strengthen central strategic management within the academic portion of the University, as well as coordination — both horizontally and vertically.**

The "Focus Area" Initiatives

The commission's first three recommendations propose initiatives in high-potential focus areas where the University already has the base and opportunity to achieve leadership if it acts rapidly. To guide and inform identification of these visible domains, the commission used the following selection criteria, stating that the "focus areas" should:

- **Be transformative.** It should have the potential to make a dramatic difference by substantially advancing knowledge and by contributing to quality of life.
- **Contribute to the University's educational mission.** The area should correlate with efforts to provide graduate and undergraduate students in-depth training strength in one area and provide a base for advances in other areas.

- **Be “ripe.”** The enabling knowledge and tools should be in place to support rapid advance.
- **Add value through synergistic interactions.** Building strength in one area should provide a base for advances in other areas.
- **Be in a field where the University can attain preeminence.** It should offer the potential for sustained leadership.
- **Build on existing strengths.** UVa already should have some of the core strengths necessary to advance the chosen area. Early leadership in an area must come from existing faculty. Additional recruitment in sub-areas may be needed to capitalize on other opportunities or to balance research and education programs.
- **Be saleable and fundable.** A broad-based constituency, both inside and outside the University, should have the resources to support initiatives in the focus area. External research funding should be available so the research component of the focus area can become self-supporting when it matures.
- **Have an academic impact across the University.** It should apply to scholarly activities in areas other than science and engineering.
- **Complement economic and social needs.** It should have the potential to contribute to the quality of life in the region, the Commonwealth and the nation.
- **Collectively, be relevant to the majority of faculty in science, engineering and medical research.** Benefits should accrue to the majority of research and education programs in these areas.

While selecting multidisciplinary areas *per se* was not a criterion, the three focus areas span multiple classic disciplines and thus could have a widespread, beneficial effect on many departments. These choices should not be viewed as new disciplines, but rather as dimensions along which scholarship in the classical disciplines is stimulated. Taken together, advancement in these areas will strengthen the majority of the science and engineering departments in the University.

The commission advocates sustained investment for at least the next decade in these three areas, with the goal that research in each area must become self-sustaining. Externally sponsored research funds would have to increase to finance the research, excluding space construction.

The commission anticipates that for each of these focus areas, compelling cases can be made to the Legislature to fund new faculty and staff positions. The continued

vitality and effectiveness of each focus area should be reevaluated periodically. Activities within a focus area may be redirected as needed, and new focus areas created as opportunities arise. Related research and education programs would naturally be absorbed into the various departments, thus strengthening them.

An important function of these organizational changes is to transform the University's culture so that choice and change become a normal part of the system. In particular, new focus areas should continue to be identified. The commission heard strong and thoughtful proposals of additional candidate focus areas that reflect the widespread strength of our faculty.

For example, a focus on sustainable development could involve projects in global-scale environment change, conservation ecology and water-quality protection. Another possible multidisciplinary area is theoretical sciences — bringing together researchers who seek to discover new theories of turbulence, complexity and non-equilibrium systems. Other such focus areas will arise. One goal in recommending new initiatives is to spawn a culture that encourages and substantively supports UVa's faculty as they move forward with major endeavors.

The commission believes that these two sets of recommendations will invigorate undergraduate and graduate programs and thus advance the research agenda. They provide a strong, coherent strategy to revitalize programs in science and engineering and ensure that the University becomes a recognized leader in the discovery and dissemination of knowledge in the 21st century. If the University deploys early investment and resources in a timely manner, then it likely can expect to have five science and engineering programs in the top-10 of the National Research Council rankings and 10 programs in the top-20 by 2020.

Details of the recommendations

1. **Create a University-wide information initiative** with the goals of building international leadership in **computer and information science and engineering (CISE)**; create CISE-catalyzed, multidisciplinary bridge programs; and develop related world-class education programs. In implementing this initiative, the University should:
 - Develop a world-class program of scholarship in computing and information science and engineering.
 - Develop world-class, multidisciplinary bridge programs between scholars in computing and information science and engineering and those in other disciplines that will transform practice and theory in each discipline.

- Augment existing CISE degree programs to create a balanced, complementary set of educational curricula centered on computation and information technology, including:
 1. A set of courses in computation and information literacy, open to all undergraduates not majoring in CISE by 2003. Computer Science 110 and Media Studies 110 are a step in that direction.
 2. Two new undergraduate degree programs: a bachelor of arts in computer science for undergraduates outside the School of Engineering and Applied who will take this program as part of a double major; and a bachelor of science in computer science degree in the College of Arts & Sciences.
 3. Innovative master's degree programs based on the scholarly work of the bridge programs and strong discipline foundations. The master's degree contemplated by the Institute for Advanced Technologies in the Humanities and the Center for Interactive Media could be the first of such degrees.
- Create an institute patterned after the Shannon Center for Advanced Studies with the goal of achieving this Information Initiative.
- Establish 50 new lines for junior and senior faculty, jointly appointed in the institute and one or more existing departments.
- Allocate enough money to support building construction, faculty recruitment and development of the overall education and research program.

1.1 -- Excellence in 'CISE' as an institutional imperative

The emergence of computer and information science and engineering, or CISE, as an intellectual discipline is a hallmark of the late 20th century. The rapid knowledge advancement in this field will exert a profound intellectual and technological influence in the 21st century. Because of the central importance of CISE, both in its own right and as a catalyst for advances in other fields, any realistic vision of the University as a great institution in the future must include world-class disciplinary excellence in CISE scholarship. Today at UVa, CISE scholars are found primarily in computer science, systems engineering, the computer engineering portion of electrical engineering and in cognitive science, based in the psychology department.

CISE involves the study of logical representation of information in forms suitable for automated processing by computing and communications machinery, as well as the design of such machinery. It also includes the algorithms and software to manage and manipulate information and the application of this technology. Major research challenges include:

- Design of software-based systems to make them easier to use and more dependable;
- Design and performance analysis of protocols for vast computer networks;
- Development of extraordinarily powerful, heterogeneous, distributed computer systems;
- Design of software architectures for ubiquitous computing;
- Design of database systems for handling petabytes (10^{18} bytes) of information;
- “Mining” of such databases for valuable information; and
- Integration of computing with biological processes.

One cannot overstate the transformative power of computer and information science and engineering. It is unique among disciplines in its potential to promote major advances in all fields. It offers revolutionary new concepts and tools for conducting research in science and engineering. Of particular importance to a university carrying Thomas Jefferson’s legacy is that CISE can bring about dramatic advances in non-technical fields. Significant progress can emerge through intellectual partnerships between leading CISE and non-CISE scholars.

Computer and information science and engineering also is enabling enormous changes in education. It is not that information technology delivers traditional information to students more effectively. Rather, such technology changes the very nature of how people interact with information and with each other. It has transformed how we teach, how we learn and how we view our educational mission.

1.2 -- Interdisciplinary partnerships and challenges

Institutions can gain an enormous competitive advantage by moving to the forefront of computer and information science and engineering in both core and multidisciplinary studies as well as in education. Nonetheless, building world-class disciplinary strength in CISE requires major effort. The market for talent is extraordinarily cutthroat, as many universities compete vigorously to build excellent CISE programs. For example, Cornell University has reorganized to promote the integration of first-rate scholarship in computer and information science and engineering and potentially all other scholarly programs. The universities of Michigan, Washington, California at San Diego, Georgia Institute of Technology and Florida State University, among others, now are investing heavily to position themselves as leaders in CISE and CISE-catalyzed multidisciplinary studies.

A second challenge is to develop a viable model for building bridges between computer and information science and engineering and other disciplines. Merely

promoting the use of off-the-shelf technology by non-CISE scholars is not a viable model. First, such technology can embody knowledge in CISE that is frequently a decade old. Second, existing tools inherently limit creative possibilities. It is the CISE scholars who have the expertise to design the new tools needed to implement the discipline's new paradigms.

To engage CISE scholars in multidisciplinary investigations, however, such partnerships must raise fundamental research issues in computer and information science and engineering. Mere programming in service to others barely interests CISE scholars. The challenge is to focus on multi-disciplinary activities that have significant potential to advance both CISE and non-CISE fields.

Many examples of such successful partnerships exist. Scholarship in CISE already has broadly changed the nature of scientific research. Modeling, visualization, algorithms and high-performance computers have established computing as a third paradigm of scientific inquiry, along with theory and experimentation. These tools allow advancement in many areas, including modeling of astrophysical processes, climate change, and pure mathematical exploration in cryptography and coding theory.

Computational modeling will contribute to both the quantum/nano and biological initiatives (the second and third recommendations). New collaborations involving a broader range of non-CISE fields can lead to additional advances. Tackling problems in diverse fields such as history, architecture, biology, law, English and religious studies with CISE scholars as partners can transform these fields and suggests new avenues for CISE research.

The University has had positive experiences with this kind of collaboration. UVa's Institute for Advanced Technology in the Humanities has propelled the University to international prominence in humanities scholarship through the novel use of computing. This success was the product of the collaboration between CISE experts and scholars in history and literature.

A similar possibility for such collaboration arises at the intersection of distributed computing theory and biological morphogenesis. Concepts in distributed algorithms and computer simulation have the potential to help biologists model how local interactions among cells lead to emergent properties, such as the macroscopic forms of organisms.

Similarly, the study of information processing in systems of cellular "machines" is suggesting new approaches to the programming of vast swarms of microscopic computers, which are soon to be realized. CISE is also a cornerstone of biological research on the human genome and proteome, as well as the investigation of cognition and consciousness in psychology and philosophy. The study of the brain and mind should provide a crucial source of future insight for CISE scholarship.

Unfortunately, the University lacks effective institutional mechanisms to create and promote the kinds of collaborations needed to propel it to world-class stature in

computer and information science and engineering and CISE-catalyzed scholarship. Although all UVa schools have activities in information technology, they are not well coordinated or based on rich interactions with CISE scholars. For example, the School of Engineering and Applied Science has no mechanism to promote hiring of CISE faculty, whose interests could support multidisciplinary collaborations with other units.

This organizational fragmentation also undermines UVa's educational efforts. School boundaries have impeded the creation of CISE majors and development of computational fluency courses for students in the College and Graduate School of Arts & Sciences. Currently, each school and department acts to optimize its own objectives and provide for its own students — as it has been asked to do. The opportunity presented by the uniquely enabling discipline of computer and information science and engineering now demands that we unify our curricular efforts.

1.3 -- The initiative and its rationale

The University-wide Information Initiative the commission proposes creating has three objectives:

- Build international leadership in computer and information science and engineering scholarship;
- Create innovative, CISE-catalyzed multidisciplinary bridge programs across the University; and
- Develop world-class education programs in CISE, computational fluency, and CISE-catalyzed, multidisciplinary studies.

To implement this initiative, the commission proposes creating an institute that would have much the same qualities and powers as the original Shannon Center for Advanced Studies. The Shannon Center sits outside all schools. It helped to establish the English department as one of the best in the world.

Employing the same techniques in science and engineering would mean hiring internationally outstanding scholars, hiring more faculty than strictly needed to support teaching obligations, paying market premium salaries, and establishing the institute as a site where current and new faculty can focus on scholarship or the creation of bridge programs.

This institute should have a director with recognized expertise in CISE and administration, a strong commitment to achieving excellence across a range of disciplines, and the resources, authority and responsibility to achieve initiative objectives. The University-wide scope of this recommendation demands such a structure.

The institute would primarily be an enabling and coordinating organization. All degrees and faculty appointments (and responsibility for tenure and promotion) would remain with departments and schools. The institute would fund faculty and staff for prearranged and limited, but renewable, terms. It would foster advancement in CISE scholarship, coordinate the creation of multidisciplinary bridge programs and centers, and oversee development of computational fluency courses so that, by 2003, all undergraduates would take computational fluency courses or have the equivalent knowledge.

Over time, 50 new tenure track faculty members at junior and senior levels would be required. This judgment is based on the need to increase the size of the existing CISE programs so they can compete with the best universities in scholarship while serving significantly expanded educational roles. Some of these faculty members should be selected in the areas needed for bridge programs. In addition, at least 20 technical personnel would be required, particularly to support experimental development in the bridge programs.

This Information Initiative also requires significant new and appropriately equipped space. The commission proposes that two buildings be funded. The first would be a state-of-the-art building to house the CISE faculty with upgraded laboratory facilities. This could be the currently proposed Information Engineering Building. Another building would be needed to house the first 10 bridge centers, several of which already exist in inadequate space. The commission strongly advocates providing space for bridge centers. In conjunction with the Digital Academic Village project, the College plans to construct a building that in part would house precisely the kind of bridge centers the commission advocates.

While the Information Initiative is grounded in scholarship, it incorporates complementary education programs to potentially touch all undergraduate students. These programs include computer fluency for all undergraduates, innovative master's degrees and minors that derive from bridge programs, as well as the undergraduate and graduate degree programs in the CISE disciplines.

1.4 -- Prospects for success

The proposal for a University-wide Information Initiative rests on two established strengths. First, it builds on substantial leadership and expertise that already exists in CISE, in such areas as distributed information system architecture, software design, system dependability, computer network protocols, computer graphics, human computer interaction, embedded and real-time computer systems, data mining, and human perception and cognition.

Second, the initiative also builds on strength in CISE-catalyzed scholarship currently under way in a variety of other disciplines. The University has three acknowledged pacesetters in this area: the Institute for the Advancement of Technology

in the Humanities, the Digital History Center and the library's E-text Center. Last year, these activities received several million dollars, including grants from the Mellon Foundation and the National Endowment for the Humanities.

Within CISE exist particular strengths in high-performance, distributed computing. Researchers have designed and built an influential meta-operating system known as *Legion*, which can harness vast computational, communications and data storage resources on the Internet. It directs them in a coordinated, secure, fault-tolerant fashion to solve the demanding computations required for applications such as drug design, cosmological simulation and protein structure analysis.

Complementing *Legion* is *Centurion*, a University-built, high-performance computer. *Centurion* integrates hundreds of cutting-edge microprocessor computers with an extremely high-bandwidth switching fabric to achieve high computational performance at a much lower cost than competing architectures.

This initiative would leverage computational modeling strengths in many fields. For instance, computer designers could collaborate with UVa astronomers who model the formation of stars, planets and black holes, as well as environmental scientists who develop quantitative models of the dynamic interaction among the atmosphere, vegetation dynamics, water, land mass and energy fluxes, and changing climate.

Significant strength also exists in the design of reliable and secure hardware and software systems. Researchers have developed techniques to inject, simulate and isolate faults in devices. The faculty has developed risk-analysis techniques and widely recognized software tools for static and dynamic reliability modeling and analysis of complex, fault-tolerant, computer-based systems.

Software design is another UVa strength. Faculty members have international reputations in safety-critical software design, formal methods, component-based software design, secure execution of mobile code, real time and embedded software, compilers, and the economics of software design. Faculty members are leaders in studying the dependability of information systems that control the nation's infrastructures, having formed partnerships with government and industry responsible for highways, railroads, banking and finance, law enforcement, and water resources. In the areas of embedded and real-time systems, UVa has efforts under way for enabling technologies such as power-aware compilers, microprocessor and memory hierarchies, security and fault detection and management, and adaptive quality-of-service for hard and soft real-time systems.

MCI recently donated \$1 million to create VintLab, a network education lab now being copied by other universities. Our network research — conducted in three different departments — covers communications and signal processing, error control, compression of data, network protocols, and efficient use of satellite, terrestrial microwave, cellular and telephone channels. The University has an award to implement T-1 connectivity to the Long-Term Ecological Research site on the Virginia Eastern Shore.

Several new multidisciplinary centers are under active discussion. The first is the Center for Interactive Media. Its focus is extending access to communities lacking such access the intellectual resources of universities. The center will explore issues such as how to use new theories on computer games and narrative interfaces to create more engaging methods for people to interact with information repositories. Ongoing research in human cognition, human computer interaction, graphics, knowledge representation, input and output devices, data mining and information retrieval provide the foundation for building a successful center.

A proposed bridge center in cognition and brain science would focus on the study of human information processing and how it relates to future computational-intensive, information-technology-rich environments. The initial foundation for this center will come from programs in cognitive psychology (perception and functional brain imaging), systems engineering and computer science (immersive environments, vision and human-computer interfaces), and neuroscience (information storage at synapses).

The third potential center would deal with bioinformatics and integrate faculty from three different schools. A human bioinformatics program will complement a partner program on plant bioinformatics at Virginia Tech. Connections among faculty in the School of Medicine's biochemistry department and the computer science and systems engineering departments in the engineering school are the basis for such a multidisciplinary center. That collaboration focuses on fundamental algorithms for pattern matching in large gene sequence databases. It can build on strengths in many important sub-areas such as data mining and statistics, mass-spectrographic protein analysis, epidemiology, computer graphics and large database management. Drawing these strengths together and augmenting them with a few key additional hires can move the University quite rapidly to prominence in bioinformatics.

2. **Establish an institute for quantum and nanoscale science and engineering** to investigate the behavior of macromolecules, materials, bio-systems and devices with nanoscale dimension; develop the tools and methods to control and manipulate these structures; and exploit the quantum properties of nanosystems to enable new paradigms for scientific measurement and technological application. In implementing this initiative, the University should:

- Fund a full-time director and administrative/technical staff.
- Recruit outstanding faculty in quantum and nano-scale science and engineering.
- Establish 15 new endowed professorships and 30 new lines for junior and senior faculty, jointly appointed in the institute and one or more existing departments.

- Secure funds to construct research and education space needed for the institute. It must include state-of-the-art, shared laboratory infrastructure for both research and instruction. Assuming approximately 1,000 square feet of research space per new faculty member and 5,000 square feet of offices equates to two buildings providing at least 50,000 square feet of space.
- Secure funds for institute faculty start-up, central experimental and computational facility expenses, and development of the overall program.

2.1 -- Challenges and opportunities

The spectacular diversity of macroscopic biological, chemical and physical properties of substances arises from complex interactions between a relatively small number of distinct atomic elements and their environments. Scientists and engineers have recognized for decades that nature exercises keen control over the composition and topology of materials at the atomic or nanometer scale. Biochemists, materials scientists, electrical engineers, physicists and basic life scientists have begun to develop methods to synthetically create nanostructures.

They fine-tune the macroscopic characteristics of materials, as well as create molecular-scale devices. Some of these nanomaterials exhibit quantum effects that promise a multitude of new technologies, ranging from novel light-emitting particles to device concepts that enable quantum-state entanglement for communications and computation.

Over the years, researchers have gradually increased the body of available knowledge about the fundamental behavior of atoms and molecules in different environments. Today, instrumentation permits researchers to see and assemble elements at the atomic level so they can test hypotheses and engineer new materials and devices.

As a result, a new field has emerged: **quantum and nanoscale science and engineering**. It involves the synthesis and control of systems whose dimensions measure only a few to a few hundred atoms (that is, 1-100 nanometers). In this size regime, properties of materials depend upon the types of atoms present, how they are assembled and the size/shape of the nanoparticle itself. As we learn how to control all of these design parameters at the atomic level, scientists are creating materials with extraordinary properties. In the life-science arena, the machinery for photosynthesis and molecular motion are amazing examples of bionanotechnology. Scientists now are attempting to create similarly active, synthetic structures. Revolutionary consequences will follow.

The frontiers of research in the life sciences, biochemistry, chemical engineering, physics, chemistry, electrical engineering, chemical engineering and materials science are being transformed by nanoscale instruments, techniques and devices. One example is quantum dots. These 10- to 50-nanometer diameter particles are made by colloidal chemistry. They emit intense light, whose color depends only on their size. This

nanotechnology may deliver displays whose resolution exceeds that of today's best photographic processes.

Another example is carbon nanotubes. Single strands of this material are only a few atoms in diameter, but can have macroscopic lengths. These nanowires have uncommon strength and novel conduction properties. In the future, they may electrically connect individual atoms or nano-objects on surfaces into circuits.

Still other applications relate to the life sciences. Most proteins, peptides and viruses are a few tens of nanometers in size and therefore are nanoscale objects. Many of the same tools used to determine structure and the mechanistic behavior of inorganic nanomaterials can also advance our understanding of the basic biochemistry of life by enabling researchers to make observations not previously possible. For instance, it is now feasible to tag biomolecules with quantum dots and optically track changes in a three-dimensional structure over time, e.g., as tissue grows. Selective protein recognition, binding and separation are also possible.

Significant advances in environmental sustainability also can be expected through development of nanostructured catalysts, atomically engineered corrosion resistant materials, nanoporous filters, and new devices for efficient solar energy storage and conversion.

To provide another example of potential impact, consider the semiconductor industry that is driving inexorably toward the nanoscale region. Increased computation rates, data-storage density and electronic data transmission speeds all are forcing devices to smaller size and more sophisticated architectures. The semiconductor industry roadmap predicts that 10 nanometer feature-sized elements will be required by 2015. Exquisite nanoscale patterning control in three dimensions will become one of the semiconductor industry's primary challenges.

2.2 -- Intellectual and technological issues

The most interesting nanoscale systems are not simply miniaturized copies of existing devices. Rather, they exploit the physics of the nanoscale to create materials with chemical and physical properties that are radically different from their macroscopic counterparts. For example, nanoscale objects have enhanced surface-to-volume ratios. They are strongly influenced by steric, electrostatic, hydrophobic and other molecular-scale interactions, producing a range of distinct chemical and physical properties. Moreover, the smallest nanoscale systems act like artificial atoms and behave according to quantum rather than the classical laws of nature. As a result, they exhibit properties influenced by wave-like interference phenomena and have quantized energy levels that are size, shape and composition dependent.

Harnessing the quantum aspects of these systems will result in new paradigms for measurement science and electronics applications. For example, advances in electronics

have resulted from control of the charge and mobility of electrons. Electrons have another property that can be manipulated: spin. A new generation of devices will emerge as researchers learn how to control spin (likely using magnetism) to build artificial structures.

Another example is particularly relevant to the Information Initiative proposed above. Currently, computers, information storage, encryption hardware, software and protocols are based on classic binary logic, relying on bits that can have values of 0 or 1. Researchers now are exploring the use of controlled quantum systems and quantum binary logic, qubits that can simultaneously have values of 0 *and* 1, for development of quantum computers and quantum information encryption and storage. Implementation of quantum encryption schemes and computational algorithms will guarantee secure transmission of information and enable solutions to problems too difficult to ever be solved on any computer-based classical architectures.

Through the emergence of such tools as scanning-tunneling and atomic-force microscopy probes, as well as optical tweezers, it is now possible to move individual atoms on a surface, create synthetic structures with atomic-scale precision, and measure extremely small interparticle forces. By combining nanostructures into composites and multilayers, one can engineer devices with properties and functionality very different from the sum of the individual parts.

2.3 -- The initiative and its rationale

The commission proposes that the University integrate and build on its many existing strengths and create an **institute for quantum and nanoscale science and engineering** under the leadership of a world-class scholar in this area. Such an institute would provide an organizational focal point for the interdisciplinary research necessary for advances in this field. The institute would be housed in newly built space in the natural science and engineering precincts. Such new space would be designed and equipped for research and graduate instruction in quantum- and nano- materials, devices and electronics, and for work in nanoscale biology.

Thirty new junior and senior faculty should be recruited in quantum and nanoscale science and technology to create a world-class facility. In addition, 15 new endowed faculty professorships should be established to provide greater incentives for attracting and retaining the best senior scientists in the area. Combined with our existing faculty, this critical mass of expertise would establish the University as one of the nation's premier facilities for nanoscale science and technology.

Although not a degree-granting organization, the institute would be an excellent resource for training future generations of scientists and engineers in this critical field as well as in the flexible research processes needed for discovery. Quantum and nanoscale science and engineering blur the boundaries between chemistry, chemical engineering, materials science, electrical engineering, physics, biomedical engineering, many aspects

of the life sciences, environmental sciences and some parts of computer science. Students actively involved in research will be trained in diverse science and engineering fields. The facilities and resources assembled would provide support for several hundred new master's and Ph.D. students. New bachelor-level degree programs in nanoscale science and technology would be extremely attractive to the high-technology industry in the region and the Commonwealth.

2.4 -- Prospects for success

Quantum and nanoscale science and engineering is ripe for investment. In recent testimony to Congress, Neal Lane, former President Clinton's adviser for science and technology (and former director of the National Science Foundation) said: "If ... asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."

The current climate for government funding in this area is very favorable, with a presidential FY 2001 budget recommendation for nanoscience and technology research almost double that of FY 2000.

The University of Virginia is well positioned to take advantage of this development. *U.S. News & World Report* already has ranked the graduate program of the department of materials science and engineering 21st in the nation. A large number of faculty in that department and others already participate in fields related to quantum and nanoscale science and engineering. Both theoretical and experimental work is ongoing in single-atom assembly and imaging, laser control of atoms and molecules, and spinelectronics (in chemistry, physics and materials science). In addition, investigations of chemical synthesis and biomolecular properties at the nanoscale currently are being pursued (in chemical and in biomedical engineering) in catalysis and biomechanical adhesion.

University researchers also are experimenting with a variety of new materials such as nanoporous aerogels and bioaerogels, nanoscale polymer building blocks, strong materials, atomic clusters, biomedical thin films and semiconducting thin films (in mechanical and aeronautical engineering, chemistry, materials science, physics and electrical engineering). They are exploring the properties and functionality of new devices based on nanomaterials, such as vertical cavity lasers, biosensors, novel magnetic data storage media, band-gap engineered photonic crystals, qubits for quantum computation and communication, biomolecular motors, and electroactive polymers.

Several departments have indicated a desire to hire faculty in this area. These hires would cement fragmented groups of excellent researchers around the University, forming a world-class Institute for Quantum and Nanoscale Science and Engineering. For example, over the next few years, the biomedical engineering department will be recruiting between two and five new faculty in related areas, as part of a development award from the Whitaker Foundation.

Support garnered from this initiative will enable the chemistry and chemical engineering departments to extend their list of distinguished faculty, each with three new recruits in nanoscale science. When combined with current and new faculty in biomedical engineering, these new researchers will establish the University as a recognized center for nanoscale research in biological systems.

Additionally, the physics department recently hired two junior faculty in quantum computing and quantum information and has been attempting to attract at least three more faculty in condensed, particularly nanoscale, systems. Linkages can be made with mathematicians in the subfields of cryptography and coding theory. Additional facilities likely will make these appointments possible, strengthening the connection to programs in electrical engineering and materials science.

Within the College and Graduate School of Arts & Sciences and the School of Engineering and Applied Science, the University has strong programs in nanostructured metals, nanoscaled semiconductors, and chemical, electronic and optical properties of surfaces. Three or four new positions in each of these areas would produce a center of international prominence while providing remarkable collaborative opportunities.

Like nanoscale systems themselves, recruiting groups of faculty into individual departments and allowing their interaction through shared building space would create an institute whose strength and breadth are much greater than the sum of its individual units. At the atomic and nanometer scale, no fundamental boundaries exist between disciplines. The tools and techniques used to manipulate atoms, particles and their mutual interactions often are independent of the basic science inquiry or final application. Establishing across disciplines a group of researchers that speak the same microscopic but different macroscopic languages would lead to collaborative activities that result in unprecedented scientific and technological advances.

Faculty members in physics, chemistry, materials science and electrical engineering have been extraordinarily successful in obtaining highly competitive multidisciplinary program funding in nanoprinting, qubit technology and giant magnetoresistance. In July 2000, the University won a \$5-million grant to create a National Science Foundation-funded Materials Research Science and Engineering Center in nanoscale materials design.

Awards increased from \$5 million in FY 1996 to more than \$12 million in FY 2000. It is not unreasonable to expect the proposed institute to obtain at least \$20 million to \$25 million of annual research support from the federal government, foundations and industry within five years. UVa has complementary educational programs that include the Science and Engineering of Laser Interactions with Matter, the IGERT program, the NSF microelectronic program, and a large educational component of the Materials Research Science and Engineering Center program.

The Virginia Legislature created a research fund last year. A persuasive example of why the state should support such research was a materials science center proposal similar to the newly funded Materials Research Science and Engineering Center. State government shows a growing appreciation for the ability of world-class research infrastructure to attract new and expanded industry to the Commonwealth. UVa anticipates that the potential for economic development in the nanoscale area will lead the Legislature to provide new funding for the needed, additional faculty. At the national level, the University may have an additional, recognizably “unfair” advantage in this area if the first extreme-ultraviolet free electron laser, a next-generation tool for nanoscale processing, is built in Charlottesville.

The breadth and scope of our existing competencies, combined with the demonstrated ability of faculty involved in this area to secure highly-competitive, multidisciplinary awards, indicate a potential for the University of Virginia to become a world-renowned institution in quantum and nanoscale science and engineering.

3. **Create an interdisciplinary biodifferentiation institute.** Its mission would be to answer the question of how cells and organisms acquire and maintain their characteristic form and function, understand how this process goes awry in disease states, and apply acquired knowledge to preserve human health. In implementing this initiative, the University should:
 - Recruit a director who is a recognized leader in a major scientific area of the institute. The director would report to the vice president for research and public service. An advisory board composed of representatives from the three schools and extramural experts would assist the director with major programmatic decisions.
 - Construct a new building (100,000 square feet) to house existing and 50 new faculty jointly appointed in the institute and one or more existing departments. Faculty recruitment should be phased. Initial recruitment of 10 faculty members in key areas, such as stem cell biology, morphogenesis and tissue engineering, would virtually assure national prominence.
 - Designate appropriate funds to support construction of the building, recruitment of faculty, and development of the overall program.

3.1 -- Challenges and opportunities

Dramatic advances during the last half-century have made it possible to define with great precision biological processes at a refined level in the realm of single cells and molecules. It is now possible to identify, isolate and manipulate genes to identify their unique functions in health and disease. The recently completed sequencing of the human

genome represents the scale of this scientific undertaking as well as the breathtaking advances that it promises.

Among the most exciting and important opportunities is to advance from the study of single units (such as cells and molecules) to the understanding of how cells and organisms acquire and maintain their characteristic form and function. Approaching the questions from the systems perspective -- rather than from that of a single cell or molecule -- will allow researchers to learn how cells integrate myriad incoming signals (physiological, mechanical and electrical), form a coherent population, establish and maintain functional form and structure, and produce stable behavior or fail, as is the case with many diseases.

Such an ambitious enterprise requires a wide range of skills encompassing many disciplines. The knowledge needed to produce this new system-level understanding includes understanding cell-cell interactions in response to mechanical, electrical and biochemical signals, genetic regulation of cell differentiation, multiscale physics-based computer simulations, nanotechnologies for micropatterning of molecules and cells in tissue engineering, and stem cell biology. The University has substantial expertise in all these areas.

3.2 -- Intellectual and technological issues

The central issue facing researchers hoping to understand biological systems can be stated as a question: "How does the information encoded in the genome interact with environmental and self-generated stimuli to produce functional and dynamically adaptive, three-dimensional structures such as tissues and organs?" And furthermore, "how is the function of those cells, tissues and organs controlled at the organismal level during development?"

For example, the stability of form that characterizes tissues and organs results from the integration of local behavior within the system. Local output, in turn, depends on global, distributed properties. It is this multiple input, multilevel processing and integrated output that life scientists have not been able to capture analytically, limiting them to measurements on individual cells or group of cells. Science has learned much about cells, but mostly as generic entities in artificial situations. We must learn about cells when they are involved in real situations, such as making or remodeling a particular tissue.

Life scientists need to answer the following major questions:

- 1. How do organisms achieve a three-dimensional structure in time?**
 - How do cells acquire their identity?
 - How do cells recognize and adapt to their environment?
 - What is the nature of forces that produce patterns and shapes in cells, tissues and organisms?
 - How do force and energy balance constrained processes?

- Can pattern and form be predicted and modeled?
- How does energy determine intra- and inter-cellular interactions?
- What are the minimal requirements, regulatory molecules, and mechanisms that control and maintain life, identity, and diversity?

2. How do biological stimuli and environment translate into a coordinated, integrated behavior?

- How does local behavior result in aggregate behavior?
- How do molecular systems process information?
- How is global integrity (homeostasis) maintained in the face of local failure?
- How are chemical processes, mechanics, and gene expression integrated to produce complex biological organs and systems with a particular function, location, size and shape?
- How do internal and external signals interact to establish and maintain identity?

Addressing these questions will promote fruitful interdisciplinary collaboration. To probe specific structures within a living tissue or organism, we would need to link with efforts in nanotechnology and robotics to help guide smart molecules and biomachines throughout the intricate landscape of a tissue. Indeed, it is possible to witness the synergistic interactions between this initiative and the information technology and nanotechnology initiatives.

This initiative also requires strengthening existing programs. Researchers in stem cell biology would be instrumental in understanding the signals that control cell identity. Researchers in chemistry and pharmacology would help design small molecules and drugs to define the function and fate of important molecules. Spectroscopists could develop new methods to visualize structural and functional changes. Material scientists could make synthetic or hybrid matrices to allow testing hypotheses about motility and adhesion in response to environments with different physical and chemical properties.

The focus area is transformative. It would advance both research and education for a wide variety of disciplines. Building on its existing strengths, the University has the potential to be at the forefront of the most exciting challenge of this new century for life sciences.

3.3 -- The initiative and its rationale

The commission proposes that the University create an **institute for biodifferentiation**. This institute would comprise a broad array of existing faculty from the School of Medicine, the School of Engineering and Applied Science and the College and Graduate School of Arts & Sciences, plus 50 new faculty and a new facility to house the institute. An eminent scholar would lead the institute.

In the pursuit of its vision, the institute would have two complementary components: **fundamental discovery** and **applied discovery**.

Fundamental discovery addresses the basic mechanisms whereby cells differentiate and arrange spatially and temporally in a structure capable of performing the specialized functions of tissues, organs and organisms.

Four overlapping and intimately related fields of knowledge would be pursued: differentiation, morphogenesis, organogenesis and systems integration. Studies would include, but not be limited to:

- Identifying the gene/protein pathways that determine and maintain cell/tissue identity in mammals as well as in more genetically tractable organisms.
- Elucidating the physical determinants of tissue/organ shape and their molecular and genetic basis.
- Defining the intracellular and environmental signals that guide and maintain tissue development and integrity, and integrated biological function.
- Studying the differentiation that occurs during tumorigenesis and wound healing.
- Understanding how cell, tissue and organ systems function at the organism level during development.

Applied discovery uses basic knowledge to generate products and techniques to enhance our capacity to conduct fundamental research, benefit human health, and stimulate our economy. The goals include:

- Producing long-lasting, fully compatible and functional tissues and organs — liver, skin, bone, kidney, pancreatic islets and blood vessels.
- Regenerating congenitally defective organs or tissues damaged by acquired disease.
- Repairing organ structure or restoring function using cell transplantation and/or gene therapy.
- Designing more effective pharmaceuticals and drugs.

In addition, these projects may lead to new diagnostic reagents for medical and research purposes, vaccines, tumoral markers, susceptibility tests (toxicants, infectious agents, environmental pollutants, bioterrorism), individualized and population-based nutritional/life-style/pharmacological interventions, and advances in DNA computing.

One and possibly two new buildings would be essential for co-locating sufficient laboratories with complementary strengths to make the institute most effective.

Common meeting and instructional facilities also are essential. Such a structure or set of structures would provide an advantage over competitors. From a practical point of view, there is no other mechanism than a new building to bring together the diverse groups of scientists required for this venture because no way currently exists to house them in existing laboratories.

Hiring the 50 new faculty to augment strength in the several fields needed for this initiative is clearly a costly and complex venture. A key feature of the proposed research focus is that the expertise required also is critical for broad-based advances in biological knowledge. This will strengthen the life sciences at the University as a whole.

The addition of five positions in morphogenesis, three positions in stem cell biology, and three positions in tissue/systems engineering would turn a currently prominent assembly of developmental biologists into a world-class group. Similar targeted hiring in cell biology, biomedical engineering and pediatrics would have similar impact. At the same time, this initiative would deliver completely new strengths to the University.

Although the institute itself would not offer degrees, it would support a lively educational mission. Students would participate in all institute activities, and that the institute could have an impact on teaching and training at all levels within the University.

Undergraduates would be exposed to new courses in such areas as physiology, organogenesis, genomics, tissue engineering and bioethics. At the graduate level, students would join the institute through existing graduate programs. Training grant opportunities would provide new sources of funding for students and attract excellent students from around the nation. At the postdoctoral level, the commission proposes creating a set of distinguished fellowships to attract the best young investigators. A yearly international symposium at the institute would focus attention on its activities and encourage interaction with key researchers around the world.

Such an institute could be created in phases, spreading the cost over time. The proposed hiring strategy and building should allow existing departments to redirect space and faculty lines so to develop other initiatives now constrained by lack of resources.

3.4 -- Prospects for success

The commission believes such an initiative would enjoy widespread success. The University already has a strong base to pursue the proposed initiative. It has leadership in four key areas — morphogenesis, bioengineering, systems physiology/pathology and organogenesis — as well as substantial strengths in applied genomics, cancer biology, signal transduction, information technology and cardiovascular biology.

UVa's expertise in proteomics and genomics is fundamental to identifying genes and proteins involved in growth and development. The application of bioinformatics will allow its scientists to assign potential functions to a gene or group of genes and guide experiments.

U.S. News & World Report ranks the departments of molecular physiology and biomedical engineering third and 15th in the nation. Strategic use of expertise in biomedical engineering, physics, mathematics and computer science would allow UVa researchers to study and model groups of genes and entire molecular pathways that control growth, morphogenesis (embryonic and evolutionary development of the structure of an organism), and remodeling of tissues in response to injury.

Based on UVa's existing strengths, faculty recruitment in several key areas should elevate the University to a position of international leadership. For instance, the Keck Center for Cellular Imaging is a leader in the technology that permits study of dynamic real-time interactions of molecules and processes in three-dimensional, live tissue over time. The free electron laser initiative, if successful, would provide the opportunity to visualize molecular interactions among cells with an unprecedented degree of resolution.

Enthusiasm for the research to be undertaken under the direction of the institute is already high at National Institutes of Health, so over the long term, grant money would be available. Indeed, several components of the proposed institute already are funded at the University. Discussion of this initiative already has resulted in submission of new research proposals. Mobilizing and organizing UVa's efforts under the auspices of a strong institute will attract additional support from the government as well as support from private donors and industry.

4. **Strategically advance excellence in science and engineering.** Support strategic new faculty appointments by providing stable, long-lived resources to fund the start-up costs of equipping and renovating associated laboratories. In implementing this initiative, the University should:

- Establish a \$100 million endowment for this purpose, to be administered competitively through the provost(s).
- Support growth in disciplines when opportunities are targeted to build excellence in areas that school and departmental strategic plans identify.
- Target opportunities across all areas of science and engineering, paying particular attention to those outside any current University initiatives, acting opportunistically and strategically.
- Request new faculty salary lines from the state, as growth requires.

4.1 -- Challenges and opportunities

The unprecedented growth of knowledge in the last 30 years has made it more difficult for academic departments to acquire expertise in all aspects of their discipline. Sub-fields have proliferated greatly in each discipline, along with an expanding body of knowledge connected with each one. While some academic departments previously may have aspired to excellence in every sub-field, the sheer cost of this effort typically makes it impossible today. Currently, departments achieve selective excellence by strategically building depth in a **set** of carefully selected sub-fields.

Despite severe fiscal constraints, the University has built clusters of strengths within many departments in science and engineering.³ Successful departments do more than build excellence; they retain the capacity to evolve and change as knowledge in their discipline changes. Departments can do this only by maintaining sufficient faculty in major sub-fields so to identify new opportunities for research and discovery as they arise. It requires strategic thought and action. Departments create strategic plans, target sub-fields for development and hire faculty — both eminent scholars and newly minted Ph.D.s — with the specific talent set they require.

4.2 -- Underlying issues

To a certain extent, size is an issue in determining a department's success. When compared with the top 20 departments in their field, the size of UVa's faculty in the natural sciences is 34 percent smaller, according to the most recent National Research Council report. This contrasts with the humanities at the University, where faculty sizes already equal or exceed the average of those ranked in the top 20. When departments are too small, they lack the critical mass needed to develop expertise around a cluster of sub-fields. They also lack the broad knowledge of their field needed to capitalize on new opportunities. Thus, it is not absolute size but **sufficient** size that is important.

Maintaining a strategically appropriate size is, of course, a matter of funding. In science and engineering, funding goes beyond finding resources for faculty salaries. In most cases, hiring faculty members requires a substantial initial start-up investment in the creation or renovation of laboratory space, in equipment, and in technical support. Depending on the experimental nature of the field and level of appointment, start-up costs range from \$50,000 to \$1 million or more per faculty member.

This commission finds that UVa science and engineering departments lack the size and resources to act strategically. Currently, the College has not filled 15 vacancies in its science departments because the lack of start-up funds precludes hiring a person

³Some of these clusters are illustrated in Appendix B on the commission's Website (<http://www.virginia.edu/virginia2020/science/science-docs1.htm>), as well as being cited as the basis for development of the three Focus-Area Initiatives.

with the right credentials. The College also anticipates 10 more retirements within the next five years.

The lack of start-up funds afflicts the engineering and medical schools in similar ways. These vacancies negatively affect teaching and research as well. Class sizes in core undergraduate courses are larger, offerings at upper-level undergraduate and graduate levels are reduced, and the increased time constraints on existing faculty impede development of innovative teaching and research projects.

4.3 -- The initiative and its rationale

The commission recommends that the University establish an endowment for the strategic investment in new faculty, an endowment that would complement the multidisciplinary focus initiatives and eventually lead to balance across the science and engineering departments. The provost(s) should allocate the proceeds from this endowment strategically and opportunistically to enhance faculty excellence. The endowment's objective should be to build UVA's science and engineering departments according to the schools' strategic plans while increasing quality in all departments.

4.4 -- Prospects for success

The success of this recommendation, as well as that of the commission's first three recommendations, rests on clusters of strengths that already exist throughout the UVA's sciences and engineering programs. The very existence of these clusters is a sign of the faculty's determination to generate new ideas and act on them. Additional faculty, allocated in support of the strategic vision now in place at the school and department level, will enable current faculty to take nationally respected programs and make them international leaders.

The recently completed capital campaign illustrated that substantial funding for faculty start-ups and facilities also can be found if donors see the importance of appointments in strategic areas. For example, significant donations were the key factor in enabling the start of a new environmental sciences building in mid-2000 that will nearly double research space and endow faculty positions. The astronomy department recently received a \$10 million gift, which will enhance its innovative program in optical and infrared instrumentation. This donation will help it participate in a world-class telescope project.

- 5. Improve the quality of Ph.D. graduate education.** Devote resources to improve the quality of graduation education and attract the nation's very best graduate students.

- Establish a \$100 million fund for graduate fellowships, out-of-state tuition remission for funded graduate students, and health-insurance benefits. The provost(s) would administer these funds, and they would be available on a competitive basis.
- Support department and university-wide initiatives to improve graduate education and attract excellent graduate students.
- Promote the professional development of students. This may involve career planning, assistance in communication to those for whom English is a second language and the study of ethics, entrepreneurship, and intellectual property management.
- Launch an aggressive, national campaign to publicize the quality of UVa's programs and to recruit exceptional graduate students.
- Expand distance-learning courses or graduate programs at distant locations as the faculty determines that on-Grounds programs are strong and stable, providing the base for projection.

5.1 -- Challenges and opportunities

Graduate education and graduate students are fundamental to the science and engineering programs at any research university. The ability of faculty to achieve its research goals depends critically on the graduate students' talent and efforts. Much of the intellectual vitality of research revolves around graduate seminar courses in which faculty and students alike probe all that is known on a particular topic. Graduate students are researchers who work side by side with their faculty mentors almost as soon as they arrive at the University. They gain expertise and experience in faculty laboratories and by tackling significant intellectual problems under the direction of senior scholars.

Graduate students also play a vital role in undergraduate education, where they serve as teachers, tutors and mentors. Graduate student teaching and participation in course laboratories greatly influence the quality and vibrancy of the undergraduate education experience. Under the direction of senior faculty, graduate students often work closely with undergraduate students in large lower-division courses.

It is also common at the University to involve undergraduates in research very early in their careers. A relationship develops among undergraduate and graduate students, who serve as role models, teammates and sometimes project managers for the undergraduates.

Universities with excellent graduate students find it easier to recruit and retain the most distinguished scholars. Owing to their pivotal role in research and in undergraduate education, the presence of outstanding graduate students is a powerful inducement for prospective faculty.

Attracting the best young people to graduate school is increasingly difficult. Impressive salaries and other benefits offered by the private sector lead many of the most

talented students, particularly in engineering, to go directly to industry or to postpone graduate education. Consequently, competition is intense among research universities for talented students who opt to continue their education.

Many peer institutions deploy considerably more resources to attract and retain these students than does the University of Virginia. For instance, Stanford University has launched a drive to secure a \$200 million endowment to support in perpetuity 300 graduate students a year in science and technology. The endowment will support each student for three years. Students receiving these fellowships are free to choose their research projects and do not depend on external funding of a research project.

On the average, UVa 's graduate students are not comparable to our truly superior undergraduates. The latest *U.S. News & World Report* ranks the graduate program of the School of Engineering and Applied Science as 36th nationally. However, UVa graduate students rank 42nd on their quantitative Graduate Record Exam scores and 39th based on their analytical GRE scores. Using these measures, the quality of UVa's graduate students depresses the school's overall standing. In addition, in some fields students come to the University to earn a master's degree, then move to a more highly ranked school for their Ph.D. This can be very disruptive to research.

The commission believes that the quest to raise the stature of science and engineering at the University can only be achieved if it develops a vigorous, coherent program to recruit and retain the very best graduate students and provide them with an exceptional educational experience.

5.2 -- Underlying issues

The University's graduate programs have several weaknesses. One is size. Departments frequently are too small to offer as wide a range of research options and graduate courses as UVa's competitors. Filling existing faculty vacancies, strategic hiring, and developing the focus areas all will help address this problem. However, the University must do much more to attract the high-quality graduate students essential to its programs.

The stipends and benefit packages offered to graduate students are barely competitive with the other universities. At UVa, graduate funding became a critical problem during the 1990s. Reductions in state support and increases in tuition during the first half of the decade rapidly added to per-student tuition costs. These financial pressures have continued, as state money for the tuition reductions of the past several years has been limited entirely to in-state undergraduate students.

Another particular problem is the inadequacy of funds known as tuition differentials to pay the difference between in-state and out-of-state tuition. Most competing institutions provide complete tuition remission for graduate students supported by fellowships, teaching assistantships or research assistantships. The University

currently provides only limited tuition remission. In particular, funds for the tuition differentials in college are inadequate and likely will become inadequate in engineering. To be competitive, departments provide tuition differentials from other funds.

Limits on funds often lead to limits on course enrollments that then constrain the breadth of graduate courses offered. Reducing graduate tuition to at least the level of in-state tuition for all students holding assistantships or fellowships is a fundamental need. In addition, most graduate programs now offer health insurance coverage to students supported by assistantships or fellowships. To be competitive, the University also must provide this benefit.

It is important to effectively publicize the graduate programs and graduate students' achievements. The University has successfully emphasized undergraduate programs, particularly in planning documents and budget requests to the state; it could use a similar approach to promote its graduate programs. It is especially important to communicate the critical role that graduate training plays in providing the staff of technology-based activities.

5.3 -- The initiative and its rationale

The quality both of the programs offered and the students attracted are inextricably related. If the University is to achieve preeminence in science and engineering, it must take steps to improve its programs and attract better students. Broadly speaking, UVa must deepen and expand the educational experiences it offers its graduate students.

The commission recommends that the University support strategic school and departmental initiatives to:

- (a) Increase the depth of graduate offerings in specific fields, and
- (b) Offer additional multidisciplinary seminars to bring graduate students from multiple departments together in their intellectual pursuits.

In some cases, departments also should allow graduate students to learn more about the transition of technology to industrial applications. This includes learning about intellectual property rights and their management. Individual departments can pursue such initiatives, or they can be multidisciplinary efforts.

Some departments now offer courses and even majors via distance learning or in areas such as Northern Virginia. Different departments elect to follow different avenues. Most, however, do not offer off-Grounds degrees, choosing to develop strength on-Grounds, before addressing new student constituencies. Distance learning is a promising avenue the University should consider for graduate programs where faculty members find it appropriate.

Finally, UVa would do well to launch an aggressive campaign directed at internal and external audiences, publicizing the quality of its graduate programs and underlining the importance of graduate education to the intellectual life of the University.

5.4 -- Prospects for success

Several innovative UVa initiatives can be viewed as prototypes for improving graduate education. The interdisciplinary neuroscience graduate program involves 49 faculty from the College and the School of Medicine. It offers students sustained support and innovative multidisciplinary courses. Competition for a place in the program is intense.

The astronomy department has embarked on a unique graduate-training program in radio astronomy instrumentation that it will integrate with its growing optical and infrared instrumentation program. It has submitted a National Science Foundation proposal with a multi-disciplinary team from the astronomy, physics, and electrical engineering departments, the Curry School of Education, and the National Radio Astronomy Observatory, housed in Charlottesville.

The Manufacturing Systems Center, established by the School of Engineering and Applied Science at the Dominion Semiconductor facility in Manassas, represents another fruitful enterprise. The first laboratory of its kind at a semiconductor plant, it provides graduate students with invaluable, first-hand exposure to quality- and process-control issues. Another program — for the "science and engineering of laser interaction with matter" — provides experience with current laser applications in industry through workshops and summer internships at national laboratories and in industry.

The University has achieved encouraging success in attracting funds to endow graduate fellowships. For instance, the College raised \$15 million for fellowships during the recent capital campaign, showing the potential exists for building such endowment programs.

6. **Establish a fund for excellence in science and technology.** Establish a long-lived fund for excellence in science and technology with a merit-based selection process to stimulate innovative research.

- Create a merit-based selection process managed from the Office of the Vice President for Research and Public Service, to be advised by a committee of outstanding faculty of all ranks.
- Select proposals to jump-start innovative research in science and engineering. One key criterion should be the potential for that research to attract externally sponsored funding as the research matures.

- Provide \$1 million in funds during the first year, increasing the fund to a steady state of \$5 million in awards annually.

6.1 -- Challenges and opportunities

To foster the innovative, speculative thinking that may form the foundations of future focus areas, UVa must encourage exploration of novel research ideas. Most external funding agencies provide awards only to those programs with track records, programs that are proven to some degree.

To help faculty members attain the standing needed to compete successfully for external funding, the University should be more entrepreneurial. It can do this by providing seed money quite early for ideas that may be too original to gain approval from traditional organizations and for groups building new focus areas. Funding truly innovative research is necessary if the University is to sustain its eminence into the future.

6.2 -- The initiative and its rationale

The commission recommends creating a "fund for excellence in science and technology" with the goal of increasing the University's leadership in science and engineering research. This money should nurture new ideas and endeavors and should not be limited to the focus areas in earlier recommendations.

In May 2000, the president of the University announced the creation of this fund, providing for \$1 million in awards for the first year. The money, however, was to some extent reallocated from other sources. The commission recommends the infusion of new money, with the intention of increasing the annual size of the fund to \$5 million over five years.

Two categories of awards should be made from this fund:

- **Exploratory awards** of up to \$10,000 should be used to support highly innovative (pilot) workshops, conferences and symposia to assess the feasibility of new ideas and their potential to develop into full-scale research efforts. Groups or individuals applying for these awards must be able to state a clear vision of their research. In some cases, exploratory awards would help teams preparing to compete for large, externally funded grants.
- **Excellence awards** of between \$50,000 and \$500,000 over several years' duration should support individual or multidisciplinary groups of investigators proposing to solve a major scientific or technological problem. The commission envisions that excellence awards would have an impact at the

local and national level and lead to important advances. Groups that applied for an exploratory award are eligible to apply for an excellence award at a later date.

The University's Office of the Vice President for Research and Public Service should manage this fund for excellence in science and technology and would be authorized to award the grants. The vice president would assemble an independent advisory committee consisting of outstanding faculty regardless of rank and, perhaps, external experts from the physical and biological sciences, engineering, medicine and other relevant fields.

A key guideline in choosing projects for excellence awards should be their potential to garner externally sponsored research funds from five to 20 or more times the fund's investment. Proposal topics could be drawn from any technical area. Faculty and students from all schools could participate in partnership with those from the sciences, engineering and medicine.

In consultation with the advisory committee, the vice president for research and public service would be responsible for developing an effective and efficient awards process. The vice president would maintain formal written criteria for selection of the two categories of awards, which might include:

- Merit of the proposed research;
- Potential for the proposed work to be the basis for an area of excellence within the University;
- Potential for subsequent extramural funding; and
- Potential for the creation of intellectual property disclosure, where appropriate.

In consultation with the advisory committee, the vice president should determine reasonable requirements for the form and content of proposals.

6.3 -- Prospects for success

This proposal is modeled after the Academic Enhancement Program, as originally defined and in the form it was particularly successful. Analysis shows that most principal investigators who received Academic Enhancement Program awards for research later received money from other sources for related research that was between five and 30 times greater than the original award. In a few cases, the externally sponsored funds exceeded a factor of 30.

Accordingly, one measure of the effectiveness of the seed fund is success in attracting additional funding for initiatives as well as the size of the resulting research

program. Although these criteria are not a direct measure of quality, they do reflect the number of students, post-doctoral students and faculty who choose to get involved in the project.

7. **Foster strategic central leadership.** Strengthen central leadership, charge it with formulating and communicating a broadly based strategy for science and engineering for the University, and empower it with resources to implement strategically important programs.
- The University should consider reestablishing a single provost who would serve as the academic leader of the entire University. This is feasible now that financial aspects of hospital management have been assigned to the executive vice president. All academic units would report to this provost, who could exercise authority more aggressively over faculty lines to achieve strategic change.
 - The University's central administration should allocate and administer new resources so that it can take cross-unit strategic actions. Patent foundation revenue is one such source of funds.
 - Each new institute should have an advisory council with at least the deans of those schools whose faculty are involved in the institute, so a forum exists to mediate between and integrate across unit interests.
 - The vice president for development should use the first six recommendations in this report for thematic, cross-unit fundraising. Schools should materially participate in cooperative theme-based development when they have common interests and in ways those interests are honored.
 - The commission should sponsor faculty discussion of alternatives for University organization that might better support its future education and research activities.

7.1 -- Challenges and opportunities

The commission believes the University is not currently organized to achieve excellence in science and technology, especially when some of the most promising areas, such as those named in the first three recommendations, are inherently multidisciplinary. The numerous departments of science and engineering are spread across three schools and administered by three deans reporting to two provosts. Most resources are controlled at a relatively low level — in schools, departments and centers.

Quite understandably, each unit head protects and advances his or her unit and allocates its resources accordingly. Administrators with responsibility that spans the units — the academic provosts and the vice president for research and public service — control only modest resources. Maintaining excellence in science and engineering requires the ability to pool resources and to deploy them to achieve strategic, cross-unit goals. Under

the current arrangement, opportunities are missed and potential synergy is sometimes lost.

The three focus-area recommendations together represent a step toward addressing these problems. Because each focus area involves faculty from at least three schools, each recommendation proposes creating an institute with substantial resources to a degree independent of any existing school. These institutes, however, are designed to focus on specific areas and should exist for as long as they have a substantive mission. The University must take additional steps to improve overall strategic cooperation more broadly among schools and departments.

The consequences of the University's decentralized organizational structure are not confined to research; they affect education as well. For example, the College of Arts & Sciences has no computer-science major, nor do undergraduates mathematics or cognitive science have much opportunity to minor in it. Because of limited resources, the School of Engineering and Applied Science can barely meet the needs of its own students for computer-science courses. Yet, the commission believes there is great interest among college students in computer-science degrees and computation literacy courses. School barriers have stunted the development of such programs.

The lack of a central strategic administrative post with both the resources and specific responsibility for science and engineering at the University also has undermined its ability to make the case for state support in these areas. UVa must be able to forcefully convey both its achievements and its needs. Since the University has a compelling vision for excellence, it needs to present it to the increasingly receptive Legislature.

The General Assembly has demanded comprehensive science and technology literacy for undergraduates and recently created a fund to support strategic university research. Legislators understand that basic research activities attract new and expanded industry to the Commonwealth. UVa's central administration needs to present better cases to the Legislature for increasing funding of science and engineering broadly, as well as for specific initiatives such as those recommended in this report. Faculty members need to participate in this activity.

7.2 -- The initiative and its rationale

The commission proposes that the University consider reestablishing a single provost who is academic leader of the entire University with overall responsibility for all education and research.

Today there are two provosts. In the past, one had academic duties combined with responsibility for hospital management. Financial aspects of hospital management recently have been assigned to the executive vice president. In this era of multidisciplinary education and research, a single academic leader would serve the University better than splitting responsibilities across two offices.

The second central office crucial to science and engineering is that of the vice president for research and public service. That office reports directly to the president and indirectly to the provost. This arrangement seems to work and should not be altered.

Central administrators should have more resources and the power to allocate them. The commission looked in depth at the allocation of the research and education budget, unit endowments, patent revenue, and indirect funds from sponsored programs. Many sources of money exist, and the deans elect to use funds from those various sources in quite different ways to achieve the greatest gain for their schools. It is not appropriate to reduce the funds available at the unit level and divert attention from pressing unit needs. Earlier recommendations specify some resources that the central offices should administer.

The provost(s) and the vice president should work closely with deans, faculty and other administrators to develop an ongoing vision for science and technology at the University and to coordinate the allocation of funds and faculty line resources. The provost(s) should more aggressively exercise authority over faculty lines to achieve strategic change.

The provost(s) should convene the strategy and decision meetings that the deans need and want. It should not be forgotten that all resources would be, in the end, allocated to activities in departments and schools. The challenge is to make the best and most highly leveraged investments of those resources.

The vice president for research and public service should have direct responsibility for overseeing the focus-area activities. Each new institute director should report to the vice president and also have an advisory council. That council should include, among others, the deans whose faculty members participate in the institute, so a forum exists to mediate between and integrate across unit interests.

The provost(s) and the vice president for research and public service must take responsibility for continually assessing barriers — organizational, financial and intellectual — to improvement in science and technology and to develop strategies to overcome them. They must develop mechanisms -- such as the fund for excellence in science and technology -- to identify areas of potential merit, mobilize resources for them and evaluate the continued viability of existing focus areas.

Finally, this commission's primary objective is to chart a vision to be the basis for fundraising. Most fundraising now is on a unit basis. Recommendations 1 through 6 of this report should emerge as development themes. The commission believes that these themes can be turned into powerful cases to attract private donations.

To be effective in raising funds for science and engineering, the University must have compelling visions. Today, those visions are naturally multidisciplinary. A cooperative development campaign, based on university-wide themes, would serve the

University better than piecemeal, restricted, unit-based fundraising. Specific focused department and school fundraising also should continue. One approach does not meet all donor interests and unit needs.

The commission discussed more sweeping school changes, such as creating a new school of science and engineering by combining the mathematics and science departments in the college with all of the engineering departments. The pros and cons of separating the science departments from the humanities departments in the college are complex and need careful consideration.

There was a suggestion to include the Ph.D.-granting science departments from the medical school as well. Although several members saw benefit in one restructuring or another, the commission was unable to build a consensus for any particular proposal. The very fact this group is recommending three focus areas, each of which spans at least three schools, is evidence that UVA's current school and department organization is not appropriate for research in science and engineering. Some members would argue that it is outmoded for education as well.

7.3 -- Prospects for success

Instances of cooperation across organizational lines have produced dramatic results. Inspired leadership led to the creation of UVA's Department of Biomedical Engineering under the joint auspices of the School of Medicine and the School of Engineering and Applied Science. This was a key element in the department's impressive win of a multi-million-dollar Whitaker Foundation grant and its high ranking in *U.S. News & World Report*.

Another significant success has been the National Science Foundation Center for Biological Timing. The School of Medicine and the College and Graduate School of Arts & Sciences pooled resources to create this center, which has consistently received high marks from outside reviewers and attracted nearly \$20 million in sponsored research funds since its inception.

Such initiatives, however, often are the result of happenstance rather than deliberation. Under the present structure, multidisciplinary ideas are difficult to initiate and implement, and consequently do not occur with the frequency needed to sustain long-term excellence in science and engineering. This recommendation is designed to enable UVA to make decisions affecting science, medicine and engineering in a more thoughtful, strategic and directed manner.

OUTCOMES

Four Questions

The University will need to deal with four questions between now and 2020 — the dawn of the University's third century — either by disregarding them or by taking action on them:

- 1. Will UVa be a respected creator of new knowledge in science and technology?**
- 2. Will it assure educational excellence for students who specialize in science and engineering?**
- 3. Will all our graduates be literate in science and technology?**
- 4. Will we capitalize on advances in information and communications technology to improve the delivery of education and the conduct of research?**

It is urgent to answer these questions in the affirmative. Now is time to act and to act strategically and rapidly. Other universities already are addressing these questions. This commission believes continued preeminence requires stronger science and engineering programs to complement UVa's strong humanities and professional programs. By providing the means to ensure this strength, the University can become a mainstay of the nation and the Commonwealth; it will foster advances contributing to the well-being and economic security of our society.

Expectations are high. The commission believes that if initial early investment and resources are deployed in a timely manner, the University will have five science and engineering disciplines in the top 10 of the National Research Council rankings and 10 disciplines in the top-20 percentile by 2020.

The Work of the Commission

The goal of the science and technology commission has been to chart a course that will substantially increase the University's excellence and leadership in science and engineering education and scholarship well before 2020. The commission includes faculty, students and representatives of other administrative offices that directly affect science and engineering, such as the University of Virginia Foundation and the Office of Development.

Members collectively span the natural and physical sciences housed in Arts & Sciences; the engineering and applied science disciplines housed in the School of Engineering and Applied Science; and the biomedical sciences (those in which the

University has a Ph.D. program) housed in the School of Medicine. The professional schools of law and business also are represented.

The scope of this commission did not include clinical health care and clinical education, except where collaboration between scientific researchers and clinicians furthers science. The disciplines addressed have extensive and fruitful relationships across the University. Directly or indirectly, the science and engineering endeavors the commission considered affect a substantial portion of the University's faculty, administration and students.

The commission met biweekly for almost two years. It sponsored a two-day workshop where deans, provosts and faculty from other universities described the methods they used to seize the initiative in science and engineering to build excellence. The group's members talked extensively with faculty, alumni, staff and administrators. Once the commission determined recommendations, its members sought to identify the attributes of each one and the resources necessary to support them. The panel also asked how the necessary resources could be obtained.