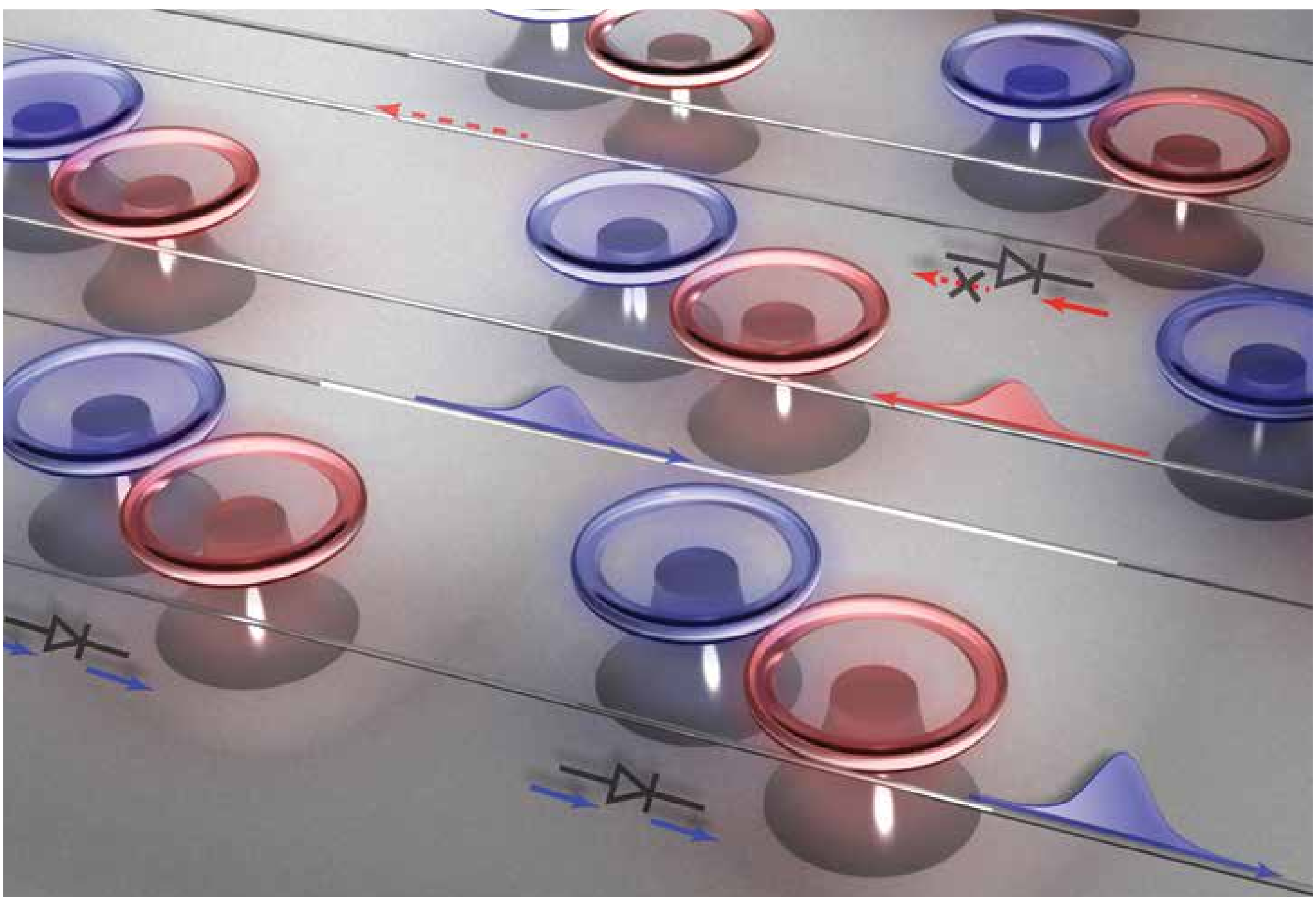
WASHINGTON UNIVERSITY MCKELVEY SCHOOL OF ENGINEERING

STRATEGIC PLAN TO ACHIEVE LEADERSHIP THROUGH EXCELLENCE

RESEARCH

Nanoscale Engineering



RESEARCH

Nanoscale Engineering

Executive Summary

Making a Huge Impact With Tiny Machines

Nanoscale engineering provides the enabling technologies for numerous applications. Clinical diagnosis can be enhanced by ultrasensitive biosensors; environmental science can leverage advanced instruments to characterize and analyze airborne particles; and medical imaging can leverage on sensors capable of detecting nanoparticles. We propose to establish a multidisciplinary nanoscale engineering program to further the development of nanoscale technologies and their applications in various fields such as medicine and environmental engineering. The program will break down traditional departmental barriers to create a critical mass of researchers that can work together across disciplines. The nanoscale engineering program will provide new research and education opportunities for our school as well as other schools that will benefit from advanced nanomaterials and devices.

The research program will span multiple layers of nanoscale technologies from materials, devices, to integrated systems. The capability to tailor and synthesize new materials with novel properties and the ability to design and fabricate advanced devices with innovative functionalities are indispensable to demonstrate enabling technologies. The program will build on our existing strength in multiple aspects of nanoscale engineering such as material synthesis, device fabrication, system integration and their applications. The nanoscale engineering program will therefore comprise three interconnected thrusts: *Nano-engineered materials, Nano-engineered devices and Nano-engineered systems for sensing, imaging and spectroscopy.* Each thrust will build on existing research strengths in the Engineering school. Furthermore, important applications in which the university has been taking a leading role will give us an edge in proving the enabling technologies developed in house. The progress and impact of the technologies in other fields will, in turn, improve the reputation of the nanoscale engineering program and catalyze the development of new enabling technologies.

To develop a world-class nanoscale engineering program, we envision the need for (1) a school-wide cluster hire of faculty in materials, devices and systems, (2) seed funding to stimulate interdisciplinary research across multiple layers of nano technologies and application domains, (3) a nanoscale engineering laboratory with cutting-edge equipment for device fabrication and system integration to complement existing facilities on campus.

Nanoscale Engineering
Washington University McKelvey School of Engineering

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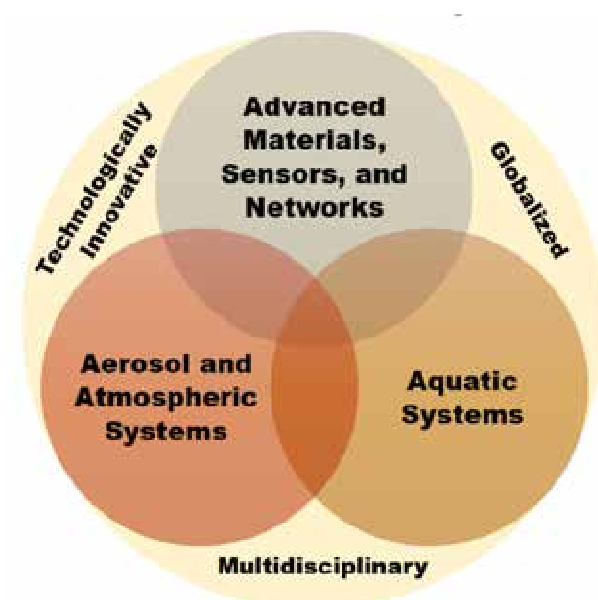
1. Overview

1.1. Smart Environmental Systems.



From local to global scales, socioeconomic development is exacerbating air quality deterioration and climate change concerns and providing a strong impetus for corresponding solutions to maintain drinking water quality and freshwater availability. Furthermore, air, water, and energy are interdependent, and their interactions influence food production, which circles back to involve environmental quality and public health. We need to address this cross-sectional relationship holistically. To describe and analyze complex environmental systems, smart systems incorporate the functions of sensing, actuation, and control. They help us make environmentally smart and sustainable decisions based on available (or new) data in a predictive or adaptive manner. <u>We propose to create a Smart Environmental Systems Center to advance our understanding of the life cycle of important nutrients and resources, augment water-energy efficiency, and improve water and air quality by using advanced materials and novel sensors and their networking capabilities.</u>

To realize this exciting opportunity, we seek to build a strong multidisciplinary team through new faculty hires and engagement of current faculty from all disciplines across the School of Engineering & Applied Science (SEAS). Environmental challenges extend beyond any one department and are best met by incorporating ongoing work on environmental research in the Department of Energy, Environmental & Chemical Engineering (EECE), advanced materials in the Department of Mechanical Engineering & Materials Science (MEMS), detection, sensing, and imaging in the departments of Biomedical Engineering (BME) and Electrical & Systems Engineering (ESE), and sensor networks, big data, and machine learning in the Department of Computer Science & Engineering (CSE). Many faculty members across SEAS and other schools at WashU have already been collaborating actively, and the creation of the new Center will further accelerate the integration of research and education in environmental systems. The Center will create dedicated testing facilities for advancing technological innovations in environmental systems from conception to prototype. Further, the Center will enhance the capabilities of our current analytical facilities, and will underpin strong external partnerships.

1.2. Mission.

We aim to create an internationally recognized, environmentally focused research Center that leverages and expands SEAS's strengths to address critical global environmental challenges. The Center will connect, facilitate, and support multidisciplinary teams within SEAS and beyond, to maximize research synergies and support greater efforts. The Smart Environmental Systems Center will integrate strong fundamental environmental science and technology with advanced materials engineering, sensor development, and the Internet of Things (IoT). This effort will include multiscale spatiotemporal measurements of contaminants, nutrients, and resources using nanoscale novel sensors and mobile platforms. Data science and networks will effectively manage the collected data, which will guide us in making environmentally smart decisions. The Center strongly supports a number of Washington University's Strategic Priorities—including Advancing Human Health, Global Engagement, Innovation and Entrepreneurship, and Energy, Environment and Sustainability — for "developing new research aimed at forging a more sustainable future" (wustl.edu/about/strategic-priorities). In addition, the Center will improve doctoral programs within SEAS through exceptionally strong integrated research-based education and will provide a ready platform for offering research outreach programs to engage with the Greater St. Louis community, industries, and international institutions. Further, the new Center will provide a distinctive advantage over peer institutes in securing research funding and attracting the first-class students who will be new global leaders in smart environmental systems.

2. Our advantages for pursuing Smart Environmental Systems

1. **As a small engineering school in a mid-sized university, we can collaborate agilely to tackle global environmental challenges.** In other words, because we are not necessarily constrained by **traditional discipline-based foci, we can conduct transformative research activities, which can achieve quantum leaps in the environmental field**. In addition, SEAS has an effective departmental structure for tackling environmental challenges. Most universities have a Department of Civil and Environmental Engineering which can trap their environmental engineers in a specific discipline and may lead to an over-emphasis on infrastructure. However, environmental research in SEAS is inherently more flexible and interdisciplinary, both within EECE and across the School and university. Current multidisciplinary collaborations across SEAS and WashU's other schools have already started to show results in successful small group funding from the National Science Foundation (NSF), the Department of Energy (DOE), the Department of Defense (DOD), the Environmental Protection Agency (EPA), the National Institutes of Health (NIH), and the National Aeronautics and Space Administration (NASA), as well as support from companies, industrial consortia, and nonprofit foundations. These collaborative efforts have also resulted in interdisciplinary joint publications in high impact journals.

2. **We have core strengths in environmental chemistry and technology.** We have recognized international excellence in (1) aerosol science and technology and (2) the chemistry of engineered aquatic systems. Eight faculty in these areas have received NSF CAREER Awards. Senior faculty consistently win major national and international prestigious awards. Further, we already have strong connections with the EPA's Testing and Evaluation Center. Even without a coordinated effort, environmental engineering is one of the highest rated SEAS graduate programs (30th nationally in 2016, 21st in 2015, and 27th in 2014 based on *U.S. News & World Report* rankings). We see a great opportunity to push this rank even higher with a critical mass of faculty conducting environmental research and improved publicity of the research and educational programs.

3. **We have eminent expertise in advanced materials and nanostructure-enabled sensors and networks for environmental systems.** SEAS has faculty who study interfacial phenomena of materials, develop novel nanomaterials, and pursue data-enabled science and engineering, sensor networks, and machine learning. In SEAS, six faculty received NSF CAREER Awards in this area. Advanced materials are central to understanding the impact of human activity on the environment. They lead to technologies for environmental sensing and continuous monitoring and remediation. Multidisciplinary efforts can allow us to make major advances to secure food and clean water for future generations. By building on our current strengths in SEAS and the Institute of Materials Science & Engineering (IMSE), we can create a world-class Center for this multidisciplinary research.

4. **We have strong schools, such as the School of Medicine and the Brown School.** A holistic assessment of the impacts of environmental systems on society can be conducted only by a stronger collaboration with these Schools. The proposed Engineering Center can be a great engine to synergistically work together to cultivate future environmentally-related initiatives.

5. **We have globalized undergraduate and graduate programs.** We can leverage the opportunity offered by the McDonnell International Scholars Academy. We already have excellent educational networks, an innovative online education platform (MAGNET), co-advised doctoral programs with the McDonnell Academy's partner institutions, international certificate programs, and undergraduate internship programs through the McDonnell Academy Global Energy and Environment Partnership (MAGEEP). These programs are a strong foundation on which to build even greater international collaboration on environmental research and education. For example, the Center for Aerosol Science and Engineering (CASE) has a network of 13 universities in seven countries working collaboratively on research and education.

6. **Geographically, we have an ideal "natural" laboratory.** St. Louis has a diverse set of natural and engineered environments that provide a context in which to study major environmental challenges. The urban portion of our setting has water quality and air quality challenges that are priorities for many old cities. Our natural systems include allow us to study means of mitigating the impacts of agriculture, industry, and resource extraction. In this large-scale laboratory, we can integrate our fundamental understanding of physico-chemical phenomena with effective monitoring, data networks, and geographic information systems (GIS).

3. Strategic research opportunities

We propose three interconnected research thrusts (3“A”s) for Smart Environmental Systems.

1. **Aquatic Systems:** Water quality in natural and engineered aquatic systems is governed by chemical, physical, and biological processes. Our research on drinking water treatments and supplies investigates processes at solid-water interfaces. This thrust will develop novel materials for water treatment and sensing, engineer new membranes for treatment processes, optimize corrosion control strategies, and guide safer aquifer storage and recovery. These research interests are closely related to the energy-water-food nexus, and we are a nationally known hub for geologic carbon sequestration research. The thrust will also investigate environmental implications of the release of engineered nanoparticles into the environment, as well as the design of environmental remediation strategies for legacy contaminants.

2. **Aerosol and Atmospheric Systems:** The field of aerosol and atmospheric systems encompasses basic principles that underlie the formation, growth, measurement, and modeling of systems of small particles in gas media. These systems are important in nature and industry, and in the study of nanoparticles that are the building blocks for nanotechnology. A new area in aerosol and atmospheric research is the development and deployment of smaller-scale, lower-cost, and more portable instrumentation and sensors for in situ environmental measurement. One particular interest is incorporation of these novel measurements on mobile platforms, such as drones or mobile laboratories.

3. **Advanced Materials, Sensors, and Networks:** Nanoscale materials-enabled environmental technology is highly promising. Advanced materials will enable us to devise more energy-efficient water treatment processes and perform more accurate sensing and imaging of contaminants and environmental parameters. Advanced sensors are of paramount importance for environmental monitoring, which can provide critical information for understanding, controlling, and protecting environmental systems. These include sensors for ultrasensitive heavy metal detection, sensor networks to monitor air pollution, and energy-efficient sensor arrays. Smart environmental systems will then leverage IoT, incorporating (1) multi-modal sensors providing real-time measurements of environmental quality, (2) wireless networks connecting myriad sensors to the Internet, and (3) analytics for modeling and predicting spatiotemporal distributions of environmental quality data. IoT-based smart environmental systems will enable intelligent environmental monitoring and management at unprecedented granularity and scales.

The three thrusts are interconnected via our strengths in real-time measurement and modeling of hard-to-access environments, new nanostructure-enabled environmental technological solutions, and sensor networks for natural and engineered systems. The holistic investigation and control of environmental systems will enable us to design smart human interfaces with dynamic environmental factors.

The new Smart Environmental Systems Center will interact with the following current WashU entities: Environmental Studies program; Arts & Sciences (e.g., Chemistry, Physics, Biology, and Earth & Planetary Science); International Center for Advanced Renewable Energy and Sustainability (I-CARES) and the associated Washington University Climate Change Program; Donald Danforth Plant Sciences Center; Tyson Research Center; MAGEEP; School of Medicine; Brown School; Institute for Public Health; and Law School. The Center will leverage the strengths in IMSE for environmental interfacial research and the Institute for School Partnership (ISP) for outreach programs in K-12 education in the greater St. Louis area.

4. Recommendations

To establish an internationally recognized, collaborative Smart Environmental Systems Center, we need to address the following challenges, seizing them as opportunities.

1. **Improve connectivity among environmentally related efforts throughout Washington University.** Environmental research and education at the university is currently decentralized. Environmental quality is an important component of I-CARES and Environmental Studies. By partnering with these programs, a new center originating within SEAS can provide a focal point for research on environmental technologies and can elevate the overall profile of environmental research at the University.

2. **Create a critical mass by hiring and connecting faculty in SEAS:** We have remarkably strong clusters in aerosols and air and water quality, but the whole may not be perceived as greater than the sum of its parts. While the Aquatic Systems thrust is recognized internationally for environmental chemistry of aquatic processes, it has only three faculty members, with a fourth to start in January 2018, and lacks a critical faculty mass for achieving the next level of achievement and improving the visibility of our accomplishments. In particular, **environmental biotechnology** and **environmental transport processes** are urgent needs. New faculty hires will allow us to extend our scope to include effective bioremediation and biological water treatment and to scale up current knowledge. In addition, while the Aerosol and Atmospheric Systems thrust has a comprehensive, broad expertise, it needs a **senior faculty hire** to advance the research thrust to a position as a global leader. Further, **across the School, technologies for Smart Environmental Systems could be a focal area for departmental searches or even a school-wide search**. Researchers in advanced materials, environmental informatics and imaging, and sensors and its networks can find SEAS attractive because of its current environmental strengths and upward trajectory. Although new hires will help to complement its much-needed expertise, connecting current faculty within SEAS is crucial. This will help us to make a bigger impact than individual departments can achieve.

3. **Provide collaborative seed funding mechanisms to actively involve colleagues in all SEAS disciplines in studying environmental systems. Provide staff to support the collaboration effort and organize the Center activities.** With the creation of collaborative seed funding, multidisciplinary teams can successfully pursue multi-PI projects and center grants. The new seed funding should encourage finding new opportunities to identify solutions to environmental challenges from a multidisciplinary perspective. So far, SEAS has strong individual researchers who have competitively secured funds for small and medium-sized projects, but we need to build synergies and sustainable networks to address environmental problems through larger-scale projects.

4. **Create testing facilities for systematic technology analyses — We need the ability to take ideas and innovation from conception to prototype.** The Center should support small to mid-size maker and testing facilities designed to investigate technologies/applications at the bench and pilot scales (i.e., a room-sized water treatment system testing setup and an atmospheric chamber for air-quality studies). The Tyson Research Center is a good testbed for natural environmental systems, but not for the engineered systems often of highest interest across SEAS. The new facilities will also provide unique teaching opportunities for new related undergraduate and graduate lab-based courses. This testing facility will also enable us to be the go-to place for industries and governmental organizations for testing and evaluating new environmental technical solutions. The Cortex community, Boeing, Monsanto/Bayer, and Black and Veatch, USDA Agricultural Research Center, and Metropolitan St. Louis Sewer District can be potential users. Moreover, there is great opportunities to collaborate with the Office of Facilities Planning and Management to install sensors to monitor buildings and environments,

effectively creating a campus-wide sensing/monitoring laboratory. In particular, we can install water and air quality sensors and monitoring networks for SEAS's new buildings, Jubel Hall and McKelvey Hall, which can be both good research facilities and excellent educational opportunities.

5. **Elevate and sustain shared instrument facilities as a major resource by hiring full-time staff and providing adequate funding for instrument maintenance and replacement.** A vigorous research facility needs full-time experts who are knowledgeable about techniques and instrumentation. Sustained support for the facility will foster broad accessibility, while maintaining technical and performance excellence. Such an environmental analysis laboratory would be a unique technical resource for the entire university and the region—supporting entrepreneurial activity, education, and outreach programs. Further, we can build on an existing solid foundation for such a shared environmental analysis laboratory, specifically the Jens Lab and the Nano Research Facility.

6. **Improve our outreach to industrial, governmental, and international organizations.** We need a liaison who can strategically connect our experts in environmental systems and these entities. We have great relationships with national laboratories and international partners, but these are not coordinated, and they happen on a professor-by-professor level. For industrial collaborations, we are not sufficiently connected to the regional community of practicing environmental engineers. To create a federally-funded engineering center, strong connections with partnerships will be pivotal.

7. **Globalize research and educational opportunities:** There are concurrent increases in the scope of environmental challenges in Asia and in the funding of environmental research by governments in Asia. WashU has (a) strong and long-running international connections and (b) internationally-recognized excellence in key environmental areas. We should develop a coherent strategy to capitalize on the increasing global resources being devoted to environmental research.

5. Metrics for success

An advisory board will be established to help us identify opportunities and provide constructive assessment of the Center. The board will include internal and external experts. The success of the Center can be judged, based on the following metrics:

1. New Multi-PI projects or research centers which we could not have gotten without this new initiative (New centers can be supported by DOD, DOE, USDA, and NSF)
2. Interdisciplinary joint papers
3. Patents and startups
4. A financially self-sufficient common research instrumental facility with a larger user-base and greater capabilities
5. Greater participation in existing international collaborative efforts in research and education and in the development of new programs
6. Strong doctoral student recruitment and placement
7. Student and faculty achievements
8. Establishment of community partners to help spread education and awareness, and promote engagement in local environmental activities