Imaging and Visualization at the University of Missouri - Columbia

It is not possible for the human brain to interpret the growing volume of research data using an exclusively numerical format. Visualization is critical. Research images bring the unseen into sight, and visualization can create new insights through the display of data. Given the huge volume of data being generated, methods that facilitate discovery and promote awareness are necessary to ensure those data are used and understood. Both imaging and visualization play a critical role in facilitating innovation – they help communicate complex concepts and support productive interpretation of large volumes of information to create new knowledge.

Our partnerships with Federal funding agencies have enabled the purchase of millions of dollars of scientific instruments, and high performance computing capacity and storage, however little has been spent on helping researchers and students visualize research outcomes, or explore new ways of combining and understanding data. The value of imaging and visualization extends across all departments, and those who benefit range from elementary students to senior researchers. With a relatively minor investment, MU can take a major leap forward helping faculty, students and staff create new visions, new images, creating new knowledge and energy.

The following group of faculty helped prepare this document for MU's Cyberinfrastructure (CI) Council as part of the 2016 updates to MU's CI Plan. The document includes a long-term vision for a "Show-Me Center for Imaging and Visualization" (see page 7) For consistency, with the other parts of the CI Plan, one and three year objectives are provided. This document is designed to help update the CI Plan, and help advance the growing momentum for a imaging and visualization center to support faculty and students from a wide-variety of discipline, and advance a variety of innovative collaborations.
Bimal Balakrishnan, Tommi White, Teresa Lever, David Larsen, Kannappan Palaniappan, Filiz Bunyak, and Chi-Ren Shyu

Imaging and Visualization and the University of Missouri (MU)

The imaging and visualization related activities at MU span multiple disciplines with differing goals. It is important to identify some of the attributes that necessitates a diversity of approaches with respect to imaging and visualization at MU. These attributes include:

1. *Areas of Scholarship:* - Nearly all the areas of academic endeavor are covered by MU's breadth of academic programs. MU brings together collaborative projects across a wide range of areas including human health, animal and human comparative medicine, plant and animal sciences, geospatial, art and design, digital humanities and engineering.
2. *Scale of* Images/Data: – The files and images range from the atomic microscopic images captured by microscopes to mammoth images of the earth and beyond captured by satellites & telescopes. They also include 3D datasets and models created using advanced CAD tools to 3D scans ranging from small artifacts to large cityscapes.
3. *Scale of* Instrumentation & Display: from the most powerful high performance computing equipment to common, handheld devices; from mobile devices to hi-res tiled displays and 3D CAVEs
4. *Source:* Captured via instruments; Constructed through data and algorithms; through use of creative modeling tools

5. *Type*: Images ranging from historical maps, photos, micrographs in 2D, 3D & 4D and graphics to visualizations constructed while you wait.
6. *Application Areas:* (archaeology to zoology, proteins to plankton, life sciences, research reactor, to urban planning). Virtually every area of research is encountering an explosion of data, and enormous challenges of comprehending the data and converting it to information. Perhaps one of the most important areas is in medical imaging, revealing 3D/4D information in a non-destructive manner.
7. *Funding agencies and organizations:* Relevant Federal funding agencies include the National Science Foundation (NSF), the National Institutes of Health (NIH), the US Department of Agriculture (USDA), Homeland Security, National Geospatial Agency, DOD, DOE and industry sponsors like Boeing and Lockheed Martin.

Return on Proposed Investment:

Images and visualization can help MU researchers and educators improve their productivity and better market their academic efforts, which in turn can lead to higher grant revenues as well as better recruitment of top quality talent. Visualization of a problem leads to a better understanding of the underlying causes and effects and often to an awareness of something that is profoundly new and unexpected. The ability to visualize complex computations and simulations is essential to insure the integrity of analysis, to achieve insights and to communicate those insights to others.

Historically, more resources have been devoted to raw megaflops for arithmetic computation rather than to imaging and visualization. Given the relatively low cost and potential, visualization is perhaps the most effective way to leverage the existing resources and planned investments in high performance computing, networking and other research cyberinfrastructure.

Imaging and visualization capabilities are increasingly important for the university's research reputation. Powerful images, videos and modeling resonate with other investigators, clarifying what others can't describe in words. Long after conferences have ended, attendees will remember that dazzling visualization from University of Missouri. Further, they will have a direct impact on the University's missions: teaching, research, extension/outreach and economic development

MU has an impressive array of talented and skilled people and a significant accumulation of useful equipment. What is needed is: alignment, coordination and support. The goal is to help MU researchers see and achieve further research outcomes. We plan to engage the various funding agencies that contribute to MU's diverse research and outreach enterprise, and foster synergistic collaborations not only across campus, and across the region, but between education and business and industry and other sectors.

Enhancements and coordination of research and clinical imaging and visualization will enhance MU's missions in a variety of ways:

- Attract and recruit top-quality graduate students and post-docs
- Support and extend MU's multidisciplinary strengths.
- Investment in imaging and visualization will have a multiplier effect on the new Data Science graduate program and Big Data initiatives at MU
- Provide exciting opportunities for MU's Development efforts.
- Help control costs – central and shared imaging and visualization resources have the potential to decrease costs for faculty start-up that might otherwise require the purchase and maintenance of duplicated equipment. For example, initial explorations have revealed there are numerous motion-capture systems across the campus.
- Provide opportunities for commercial collaborations that will open untapped federal funding sources directed at industry partnerships.
- Help advance Missouri's industrial competitiveness and economic development. For example, visualization technologies and methods have proven effective in reducing costs involved in the iterative design process.

Table – 1. MU experts whose research interests involve imaging and/or visualization

Area(s) of Expertise	**Investigator**	**Department**
Protein Structure Determination via Cryo-Electron Microscopy	Tommi A. White, Ph.D.	Electron Microscopy Core
Materials Science Analytical Electron Microscopy and Microanalysis	Thomas F. Lam, Ph.D.	Electron Microscopy Core
Geological Sciences Imaging & Microanalysis	James Schiffbauer, Ph.D.	Geological Sciences
Electron Microscopy for Cell Biology	Martin Schauflinger, Ph.D.	Electron Microscopy Core
Light & Confocal Microscopy	Aleksandr Jurkevic, Ph.D. Tom Phillips/Antje Hesse	Molecular Cytology Core
Automation and Pipeline Data Processing	Scott Givan, Ph.D. & Christopher Bottoms, Ph.D.	Informatics Research Core
Single Molecule FRET	Peter Cornish, Ph.D.	Biochemistry
Atomic Force Microscopy	Gavin King, Ph.D.	Physics
Biomedical Image Analysis	Filiz Bunyak, Ph.D.	Computer Science
Image Analysis & Algorithm Dev	K. Palaniappan, Ph.D.	Computer Science, CIVA Lab
Histopathology	Dimitry Shin, Ph.D.	Pathology & Anatomical Sci.
"Image Analytics, Visualization, & Eye Tracking	Ilker Ersoy, Ph.D.	Pathology & Anatomical Sci.
Information Behavior in Medical Imaging	Carla Allen	Clinical and Diagnostic Sciences

Spatial abilities in ultrasound proficiency	Doug Clem, Ph.D.	Clinical and Diagnostic Sciences
Visual Story Telling in Health Behaviors	Michelle Teti, Ph.D.	Health Sciences
Anatomical variants and comparative modalities in sectional imaging	Patricia Tew	Clinical and Diagnostic Sciences
Motion analysis and computer modeling in physical rehabilitation	Trent Guess, Ph.D.	Physical Therapy
Big Data & Image Informatics	Chi-Ren Shyu, Ph.D.	Electrical/Computer Engin. & MU Informatics Institute
MRI/PET	Timothy Hoffman, Ph.D.	VA Biomedical Imaging Ctr
Neutron Imaging/Scattering/Diffraction	Tom Heitmann/Helmut Kaiser/Haskell Taub	MU Research Reactor/ Physics & Astronomy
X-ray Diffraction	Paul Micelli/Jack Tanner	Physics & Astronomy
Auger Spectroscopy	Patrick Pinhero, Ph.D.	Chem Engineering
Raman Spectroscopy (SERS)	Xudong Fan, Hao Li	BioEng/MAE
Planetary Nebulae	Angela Speck, Ph.D.	Astrophysics
Sensory perception, motion analysis	Marjorie Skubic, Ph.D.	Computer Science
Robotics & robotic vision, HCI,	Guilherme DeSouza, Ph.D.	Computer Science, ViGIR Lab
Design visualization & simulation	Bimal Balakrishnan, Ph.D.	iLab/ Architectural Studies
High-resolution digital aerial photogrammetry	David Larsen, Ph.D.	Forestry, Natural Resources
Light microscopy, eletrophysiology	Teresa Lever, Ph.D.	Communication Science & Disorders
Paleobiology	John Huntley, Ph.D.	Geological Sciences
Siesmology	Eric Sandvol, Ph.D.	Geological Sciences
Digital Humanities	Twyla Gibson, Ph.D.	SISLT
User Experience Research; Information Behavior	Sanda Erdelez, Ph.D.	Information Experience Lab; SISLT
Human Factors; Eye-Tracking	Jung Hyup Kim, Ph.D.	Industrial Engineering
CAD/CAM	Luis G. Occeña, Ph.D.	Industrial Engineering
Geospatial Intelligence, GIS, Transportation Simulation	Timothy Matisziw, Ph.D.	Civil Engineering & Geography
Traffic Engineering; Driving Simulators	Carlos Sun, Ph.D.	Civil Engineering, Transportation Lab
Traffic Simulation, Driver Behavior	Praveen Edara, Ph.D.	Civil Engineering, Transportation Lab
Planar Laser Induced	Jacob A. McFarland, Ph.D.	Mechanical & Aerospace Eng.

Fluorescence & Particle Imaging Velocimetry		
2D & 3D Scanning	Marcello Mogetta. Ph.D.	Archaeology
Remote Sensing & Geophysical tools	Francisco "Paco" Gomez, Ph.D.	Geological Sciences
360 video & VR for journalism	Clyde Bentley	Journalism
360 video & VR for journalism	Mike McKean	Journalism

Note: Includes faculty whose research involve and can benefit from visualization and imaging.

Imaging and Visualization Needs and Recommendations

Note: as described on page 1, these recommendations are intended to advance MU toward the Show-Me Center for Imaging and Visualization described starting on page 7. However, they are not dependent on that center, and should be used to coordinate and guide the one and three year objectives and actions relative to the update to MU's Cyberinfrastructure (CI) Plan

Cross connections with other areas of emphasis in the MU Cyberinfrastructure Plan

As the various components of MU Cyberinfrastructure Plan are developed, we expect that there will be overlap with the life sciences, geospatial and digital humanities components. All of these will be enhanced through coordination and support. For example, all of these areas have identified the need for a 'concierge' type role that can help researchers find and effectively take advantage of relevant resources and expertise.

<u>One Year Objectives</u>

1) Investigate how a central shared facility might achieve a better return on investment of equipment – for example duplicated motion-capture equipment, and equipment with a useful life beyond the project that funded its purchase.
2) Build a community of researchers, IT professionals, and students interested in imaging and visualization.
    - Gather and promote information on the imaging and visualization expertise at MU.
    - Develop a network of interested companies and organizations with complimentary interests or resources.
    - Facilitate group collaboration through regular meetings and outreach opportunities, lab tours, etc. that focus on building capacity and pursuing relevant funding opportunities.
    - Help assure relevant training and support is available.
    - Engage students in experiential learning.
    - Gather information on the relevant collections of images (i.e. Journalism School's Picture of the Year, historical images, State Historical Society, maps, TV etc.)
    - Engage and advance resources available through MU's participation in the Advanced Cyberinfrastructure Research and Education Facilitator (ACI-REF) program (https://rc.fas.harvard.edu/partnerships/aci-ref/) Xsede (Extreme Science and Engineering Discovery Environment (https://www.xsede.org), the Great Plains Network, and other multi-campus collaborations.
    - Build and strengthen industry ties and opportunities for commercialization in collaboration with OTMIR & Missouri Innovation Center

3) Discern the needed infrastructure and how it can be increased incrementally as demand and funding increase.
   - Develop relevant hardware and software configuration specifications to help ensure acquisitions avoid fragmentation and help enable efficient support, training and maintenance.
   - Evaluate and assure cost-effective equipment purchases are made. Use resources set aside for CI Council endorsed "Special Projects" to explore how HPC, disk storage and high speed networking requirements can be exploited and increased. An example of relevant question is how large numbers of GPU (graphical processors) could be used to do visualization remotely.
   - Research projects underway at MU will be engaged in the process to evaluate, explore and demonstrate the technology possibilities and best approach for scalability and sustainability.

4) Develop a Strategic Plan for a collaborative imaging and visualization center that will encourage innovation and pursue a sustainable business model.
   - Produce marketing-oriented content to help raise awareness and for fund raising
   - Assure MU development organization is aligned to promote the multidisciplinary center.

<u>Three to Five Year Objectives</u>

1. Lay the groundwork for, and create a center for imaging and visualization, which brings together infrastructure and expertise under one roof in a location accessible to researchers on campus.
2. Hire a dedicated person whose job it is to make the Show Me Center a sustainable reality and coordinate its activities.

Preliminary Estimates of Space Needs for Imaging and Visualization at the University of Missouri	
Space (Square Feet)	Purpose
250	Cintiq HD animator workstations (5-10). Assuming 5' x 5' for each work station 25 ft2 x 10
150	conference room for discussion and visualization 10' x 15'
400	2- 5 staff offices 10x8'= 80 ft2 x 5
1600	computer lab desks and computers with access to compute nodes, visualization software etc for facilitating both group and individual work. Big flat panels for remote display 40 x 40
1000	hi-res tiled display (such as a 10 x4 with a total of 40 panels) with space in front of it for meetings/ discussion etc.
1600	(minimum) if plan to include a CAVE like facility using desktop VR system or a variation with 3 angled screens (includes service space and audience seating)
100	3D printer
3.500	Subtotal
900	Approximately 25% for service spaces, corridors, etc.
4,400	Total

NOTE: To create a system that has projected floors and ceilings for a Virtual Reality facility, will need a space three floors high - likely best done in a custom built facility

The Big Picture: the Show-Me Center for Imaging and Visualization

Cutting-edge imaging technologies in the United States are mostly located on the coasts, with a few scattered about the middle of the US. These closer centers lack a comprehensive suite of instrumentation, or image analysis expertise, or both for investigators to fully benefit from these technologies. Often times, these imaging centers were put together as an after-thought being spread throughout an academic campus with no consistency, oversight or management. The proposed Show Me Center will meet these demands. This facility will set the bar for imaging and analysis, which requires the following for the Midwest Imaging Center to be a success:

1. Instruments will be housed under the same roof
2. Dedicated experts will operate the instruments, consult and provide service.
3. UM System-wide support

As the flagship of the UM System, University of Missouri is an ideal candidate to realize this center. Centrally located in the heart of the Midwest, Columbia is easily accessible with a regional airport or shuttle services to/from international airports. Additionally, there is existing expertise on campus for a number of desired imaging techniques and analysis (see Table 1). The Center should house a suite of instrumentation that seeks to serve the broadest community of scientists, here at home and regionally. Primary areas of focus should be identified in the future (such as life, materials, geological, nanofabrication).

Physical Space

The physical space designed to house the Show Me Center would be located in a building suited for sensitive imaging equipment. The rooms housing sensitive equipment would meet instrumentation manufacturer's specifications in acoustics, vibrations, electro-magnetic interference, temperature/airflow, humidity, etc. A more-secure area would house the most sensitive instrumentation (electron microscopes, atomic force microscopes, MRI). The facility would also include preparatory labs and offices. On the upper floors, less sensitive equipment could be housed (light, confocal microscopes), interspersed with offices and preparatory lab space including a clean room for microfabrication. Space to accommodate image processing expertise, visualization tools, computational analysis and meeting rooms would also be included.

Where to Start and Why?

While the proposed Show Me Center will require significant investment (see following table) we can start by capitalizing on and sharing existing instrumentation and expertise currently available at University of Missouri. MU has already attracted some of the best investigators. Realizing this center will not only retain them, but attract other great investigators and graduate students who will expand MU's research knowledge, capabilities and success. The center will enhance instruction by allowing students access to cutting-edge, state-of-the-art imaging and analytics, both in theory and application. Through workshops, courses, and trainings, the Center will become nationally recognized for contributions in the area of imaging and image analytics.

The center will improve efficiency and effectiveness as similar instrumentation/expertise can be housed together, collaboration will be fostered and better science can happen. This boost in research infrastructure will provide the right tools to answer the research questions, facilitating publications and assist with securing and maintaining grant funding. Also, this center will enhance the region's economic development and expand the System's research capabilities. All these attributes are in accordance with the UM-System's strategic priorities and initiatives.

Imaging instrumentation needed at MU		
Area of Imaging	**Cost**	**Nearest Instrument**
Dedicated Cryo-TEM	$5,000,000	West Lafayette, IN
Focused Ion Beam SEM	$2,000,000	Rolla, MO
Atomic Force Microscope	$300,000	Columbia, MO
High Pressure Freezer	$350,000	St. Louis, MO
Cryo-stage for SEM	$200,000	East Lansing, Michigan
X-ray photoelectron Spectroscopy	$800,000	Rolla, MO
Secondary Ion Mass Spectrometry	$2,500,000	St. Louis, MO
Micro-CT, Nano Tomography	$1,000,000	Kansas City, MO
X-ray Diffraction	$500,000	Rolla, MO
Super-resolution light microscopy	$1,000,000	St. Louis, MO
Integrated automated mineralogy and petrography	$1,000,000	Golden, Colorado
Dedicated Electron Beam Lithography	$1,000,000	Urbana, IL

Visualization Related Infrastructure needed at MU

In contrast to imaging centers, there are some leading visualization centers in the Midwest. MU can benefit from existing ties many MU faculty have with these centers to enhance visualization capabilities at MU. Currently visualization data capture equipment is distributed across campus and maintained by individual PIs. Challenges identified during the CI plan discussion include lack of awareness about existing resources, inconvenient location of resources and lack of norms/ expectations to encourage sharing. Perspectives collected from faculty (See Appendix A) indicate additional instrumentation and technology needs including mobile instrumentation for field studies.

In addition, visualization research involves need for a variety of display platforms. While MU has a variety of 3D displays in the iLab, we lack two significant display environments compared to other research institutions (See Appendix – C). MU will benefit from a high resolution tiled display and a full-fledged CAVE facility which can support a variety of data visualization needs in architecture, engineering, geography, geology etc.
Current needs include:

- 3D Scanning and digitizing tools
    - Terrestrial LiDAR
    - FARO Focus3D 3D scanner ($43,000+)
    - Creaform hand held 3D scanner ($75,000)
    - GOM ATOS CORE 185/80 blue light scanner ($100,000)
- High-Resolution, 3D tiled displays ($120,000 for a 3 x 3, 3D tiled wall; Will cost more depending on size and number of tiles)
- CAVE-like facility based on Desktop VR approach with tracking ($300,000 to 500,000)

Computation, Data Storage and Networking needs

To be clarified and understood through MU's CI Council's Cyberinfrastructure Plan Updates. Special Projects activities will begin in 2016.

Management, Staffing, Training and Support

The proposed Show Me Center would have a director who leads the mission and vision, guided by an oversight advisory committee to determine policy and where applicable configure a rate structure for cost-recovery. Administrative staff will more efficiently serve as the initial point of contact, assure coordination, and perform fiscal duties. It is expected instrumentation would be managed by the Facility Online Manager reservation and billing system, which has worked well MU's Electron Microscopy Core Facility. This system allows users to reserve their instrument usage appointments online. Usage time is tracked automatically and billing reports can be generated at any time. Each instrument would have at least one, if not two, instrument managers that can provide training and assistance on the instrument if needed.

Needed expertise

Note: Many of these skilled personnel may already be available on campus as post docs, research scientists and doctoral students

- Instrument operations for imaging
    - The more sensitive and valuable instruments require a dedicated operator with 2-5 years of experience on the particular instrument. A Ph.D. is preferred for the instrument operator, but minimally it requires a bachelors. Ideally, operators will have relevant previous experience and be familiar with a number of different specimens. To cross-train, and develop their knowledge and skills, instrument managers will work together.
- Image processing
- Computer vision
- Pattern recognition
- 3D modeling, animation,
- Motion capture and analysis
- 3D simulations and gaming

Appendix A:
Faculty Perspectives on the Importance of Visualization on Research and Teaching at MU

Archaeology: Dr. Marcello Mogetta
Since 2009, I have been conducting a major archaeological excavation at the ancient city of Gabii (Italy), collecting 1TB of digital data in the form of photographs, scanned plans, surveyed measurements, written descriptions and 3D models capturing stratigraphic layers and features such as walls. My team is continuing to build photorealistic georeferenced models, which provide a much more intuitive experience of the archaeological record, for researchers working on the project, for academics studying it, and for the general public. The goal is to make these models a core part of our publication strategy, subjecting data visualization to the same level of scrutiny as text. The first pilot publication is in preparation with the University of Michigan Press. This will represent the first of a series of final reports, which will appear as other areas of the excavation are completed. In this context, the continued development of user interfaces is crucial to the success of the initiative, and, more broadly, to the acceptance of new standards for peer reviewed publication of projects in any field using 3D modeling and visualization as research and dissemination tools.

More recently, I launched a new project of high-resolution, high-precision 2D and 3D data capturing to maximize the research potential of a sample of pottery vessels currently stored in MU Museum of Art and Archaeology, on temporary loan from the Musei Capitolini in Rome. The specific aim is to apply techniques of digital visualization to the study of function, use, and re-use of these vessels (e.g., identifying features like intersecting incisions in the fabric from multiple actions or moments of use, and the locations of these marks of past use). This information would integrate with and complement previous research on these vessels (which elucidates the production of these ceramics and their distribution patterns), thus reconstructing the entire life cycle of the artifacts. The results will be presented through an interactive online scholarly catalogue, making both the 3D models and the scientific results available to the research community and the broader public in visually different ways.

Advanced digital imaging and visualization methods play an important role in my current research projects. The creation of a centralized resource at Mizzou would support my initiatives in a significant way, providing additional access to software, technology, and expertise. Such a unit would represent a valuable asset to attract and train future graduate students who would become involved in my research projects.

Geology: Francisco "Paco" Gomez
My paleontology colleagues (John Huntley and Jim Schiffbauer who look at small things) are definitely interested in visualization. Similarly, my volcanology colleague (Alan Whittington) also has interests. At the very big scale, my seismology colleague (Eric Sandvol) has interests in visualizing large data volumes of the earth's upper structure. I have a ground-based imaging radar (used primarily for interferometry) (http://tectonics.geosc.missouri.edu/gbir_intro.html. I do not have a terrestrial LiDAR, although I would be interested in using (and acquiring) one. On the issue of Photogrammetry, I have just successfully created a good point cloud model using composited, high-resolution photos ('giga-pixel' panorama photos). This works well for non-vegetated surfaces such as rock faces, rock falls, architecture, etc.

Department of Veterinary Medicine & Surgery and Radiology and International Institute of Nano & Molecular Medicine - Charles A. Maitz, DVM, PhD, DACVR-RO

A primary mission of the Department of Veterinary Medicine and Surgery is to develop and disseminate knowledge to improve the health and well-being of animals and people through instruction, innovative research, service, and leadership. As diagnostic and research capabilities grow, so does the need for visualization of the gathered information. In day-to-day operations, the Veterinary Health Center utilizes some of the most advanced diagnostic imaging equipment available, including computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET). Advances in visualization not only improve our ability to diagnose and evaluate diseases, but also allow us to better educate veterinary students and residents. Furthermore, computer visualization is of great importance to our research efforts. As a campus, we are uniquely equipped for the development of novel radiopharmaceuticals. At the College of Veterinary Medicine, we seek advances in visualization to allow us to assess the information from scans of multiple metabolic pathways to improve targeted therapies to tumors while sparing normal tissues from harmful effects. Additional research projects include investigation into the "-omics", be it radiomics, genomics, epigenomics, or proteomics. All of the "-omics" research foci require analysis of very large data sets, and are grouped under the umbrella term "big data." Visualization of this data is of critical importance to the evaluation and classification of results, leading to better understanding of disease processes in both animals and humans. Improved resources in visualization would allow for improvement in the number and quality of grant awards and publications, while also improving the learning experience for students in our department. While developing a plan for managing the needs of the University, please keep the activities of the Department of Veterinary Medicine and Surgery in mind.

Appendix B:
Comparable Imaging Facilities

Imaging Facilities similar to the proposed, Institution, location and Expertise.

Facility	Institution & Location	Expertise
Central Microscopy Research Facility	University of Iowa Iowa City, IA	Life & Materials
GW Nanofabrication and Imaging Center	George Washington University, Washington, DC	Life & Materials
University Imaging Centers & Characterization Facility	University of Minnesota Minneapolis, MN	Life &Materials
Atomic and Nanoscale Characterization Experimental Center (NU*ANCE*)	Northwestern University Chicago, IL	Materials Science
Center for Electron Microscopy and Analysis	Ohio State University Columbus, OH	Materials Science
Microscopy & Image Analysis Laboratory	University of Michigan, Ann Arbor, MI	Life Sciences
National Center for Microscopy and Imaging Research	UC- San Diego San Diego, CA	Life Sciences
Cambridge Advanced Imaging Centre	University of Cambridge, UK	Life Sciences
Center for Microscopy & Image Analysis	University of Zurich Zurich, Switzerland	Life Sciences

The imaging facility that most closely resembles what is proposed for MU is the University of Iowa's Central Microscopy Research Facility. Housing light, confocal, atomic force, and electron microscopes, as well as spectroscopy including Raman and X-ray photoelectron and X-ray energy dispersive spectroscopy. Lacking in Iowa is a centralized facility, clean room and image processing expertise. George Washington University recently partnered with FEI to provide the Nanofabrication and Imaging Center, which is poised to be a great resource in the region, however is currently lacking image analytics. University of Minnesota comes in next, however the life (UIC) and material sciences (CharFac) instrumentation are in separate locations on separate websites. Similarly, Northwestern University has separate life (BIF, CAM) and materials science imaging (NU*ANCE*) as does Ohio State, which is an FEI Center. Some impressive international life sciences imaging & analysis centers included the Universities of Cambridge and Zurich.

Appendix C:
Visualization Centers at Major Research Universities

Visualization Lab@ Research Computing – Princeton University
http://www.princeton.edu/researchcomputing/vis-lab

The Princeton Institute for Computational Science and Engineering and the Office of Information Technology work together to provide the computational and digital data infrastructure necessary to support research by faculty, researchers and students. The resources and services provided centrally include: computational and visualization hardware, software, system administration, programming, and visualization support. The Terascale Infrastructure for Groundbreaking Research in Science and Engineering (TIGRESS) High Performance Computing Center and Visualization Laboratory at Princeton University is a collaborative facility that brings together funding, support, and participation from a number of institutes, academic departments and faculty members. The facility is designed to create a well balanced set of High Performance Computing resources meeting the broad computational requirements of Princeton's research community. Contributing faculty and departments are guaranteed access to the systems based on their contributions. Other researchers can gain access to the resources through a proposal process. The visualization lab is located adjacent to the research computing staff offices and provides advanced visualization resources, including a high-resolution display wall and support for scientific visualization and geospatial codes on various platforms. Visualization applications supported by their research computing team range from individual desktop applications to scientific visualization applications running in parallel on resources at remote supercomputing centers. They also support geospatial computing and analysis. They have dedicated walk-in help sessions each week for visualization support related to applications, data formats as well as visualization and display techniques.

Research Computing Center Data Visualization Laboratory – University of Chicago
https://rcc.uchicago.edu/resources/visualization

The University of Chicago's Research Computing Center (RCC) maintains data visualization resources including high-end 3D graphics processing and display hardware, commercial and open-source data visualization software, and custom remote visualization tools for in-situ visualization of data stored on RCC's compute cluster and are broadly available. Consultants provide training on visualization software, and develop customized data-visualization tools, and are available to help develop effective data visualizations and customized data visualization tools. The RCC Data Visualization Laboratory is outfitted with a high-performance visualization workstation equipped with an Nvidia Quadro 5000 GPU and a high-performance 6 TB locally attached disk array. It is coupled with a ProjectionDesign F35 AS3D active stereoscopic projector which provides a 2.3 MPixel active-3D display. In addition to the visualization hardware and local storage in the lab, the workstation is connected to the RCC compute cluster and storage system, providing straightforward access to research data and introducing the possibility of interactive supercomputing. A locally developed visualization tool called Sviz allows users to run graphics-intensive applications remotely with graphical output sent to one's local machine. The Sviz server runs on Midway's high-performance GPU-equipped compute nodes, so one can run high-end visualization software regardless of local hardware capabilities. One can visualize data stored on Midway without transferring the data to a local visualization workstation

Center for Research Computing Visualization Lab – Rice University
http://viz.rice.edu/ and https://www.crc.rice.edu/visualization/

At Rice's Chevron Visualization Laboratory, scientists and students can interact with data on a 200-inch, 3-D screen. The NSF-funded DAVinCI Visualization Wall consists of 16 stackable active 3D from Barco arranged in a 4 x 4 array. The display measures 14 feet by 8 feet with a display resolution of 7680×4320, totaling more than 33 million pixels viewable using active shutter glasses. An IR-based Vicon system provides 3D tracking capabilities for applications. The wall is driven by a pair of large memory servers. One hosts a pair of nvidia quadro plex 7000 graphics units and runs RedHat Enterprise Linux, while the other has four nvidia quadro k5000 cards and runs Windows 7. A dedicated 10Gb connection to the Rice Primary Data Center provides access to additional DAVinCI cluster resources including GPU nodes and a gpfs parallel file system. The visualization wall enables scientists to project data into three dimensions to probe details in ways that were not possible before, and users can display and analyze images of all types, from atoms to galaxies.

Envision Center Information Technology at Purdue
https://www.rcac.purdue.edu/envision/dataviz/

The Envision Center, a part of the Information Technology at Purdue (ITaP) offers a range of visualization services and support for communicating complex research ideas. Their work integrates computer graphics, advanced visualization, auditory (sound), haptic (touch), and multimodal interaction and high performance computation. They provide services including data visualization and analysis, virtual simulation, human-computer interaction and media creation for communication. The center hosts a reconfigurable CAVE display with three vertical screens and floor with stereoscopic 3D displays. The adjustable outer display walls accommodate a variety of use cases. The center also has a fully-portable visualization system using 3D television paired with Microsoft Kinect®, Razer Hydra®, and Novint Falcon® for interactivity.

Texas Advanced Computing Center (TACC) – Visualization Lab
https://www.tacc.utexas.edu/vislab

The Texas Advanced Computing Center (TACC) provides advanced visualization resources and consulting at their Visualization Laboratory (Vislab). The Vislab staff assist researchers in exploring issues related to large-scale visual analysis and human perception. It offers opportunities for UT faculty, staff and students to use visualization, interaction and computational resources to explore and present data. Their work is facilitated by a variety of state-of-the-art visualization and display infrastructure which provides a platform for technology development related to visualization.

Key visualization infrastructure include:

- Stallion hi-res tiled display system is one of the world's highest resolution tiled-displays with an aggregate resolution of 328 megapixels enabling visualizations with great level of detail. The display is comprised of Dell 30-inch flat panels in a 16 x 5 configuration. The supporting cluster allows users access to over 82GB of graphics memory, 1.4TB of system memory, 21TB aggregate local disk storage, and 256 processing cores which enables the processing of datasets at massive scale, and the interactive visualization of substantial geometries. A large, shared file system is available to enable the storage of terascale size datasets. Locally developed software includes DisplayCluster, MostPixelsEver and Cluster Edition which allows the distributed display to be controlled easily.
- Lasso is a multi-touch, tiled display comprising six 46" monitors in a 3 x 2 grid configuration. The effective 12.4 megapixel display is augmented by the PQ Labs 32-point multi-touch infrared perimeter, allowing seamless multi-touch across the display surface. Microsoft Kinect displays provide touch-less, gesture based interaction.
- Bronco flat screen display gives users a 20 ft. x 11 ft., 4096 x 2160 (4K x 2K) resolution display, powered by a Sony SRX-S105 overhead projector. The display is supported by a high-end Dell workstation making it accessible for a wide variety of applications. It is configurable to accept inputs from up to four simultaneous video sources.

Center for Computation and Visualization – Brown University
https://www.ccv.brown.edu/technologies/visualization

Visualization services provided by Brown University's Center for Computation and Visualization (CCV) include:

- immersive high-end visualization technology including the YURT (360° VR display) and the CAVE
- expertise in graphics software and packages
- custom software development and consultation on technology implementation for visualization

The visualization infrastructure that is supported by CCV include:

- The YURT – 360° VR display (https://www.ccv.brown.edu/node/124)
- CAVE (https://www.ccv.brown.edu/node/125)