Editor: Theresa-Marie Rhyne

NIH-NSF Visualization Research Challenges Report Summary

Tamara Munzner
University of British Columbia

Chris Johnson
University of Utah

Robert Moorhead
Mississippi State University

Hanspeter Pfister
Mitsubishi Electric Research Laboratories

Penny Rheingans
University of Maryland, Baltimore County

Terry S. Yoo
National Library of Medicine

Nearly 20 years ago, the US National Science Foundation (NSF) convened a panel to report on the potential of visualization as a new technology.[1] Last year, the NSF and US National Institutes of Health (NIH) convened the Visualization Research Challenges (VRC) Executive Committee—which was made up of the authors of this article—to write a new report. Here, we summarize that new VRC report, available in full at http://tab.computer.org/vgtc/vrc and in print.[2]

The goals of this new report are to

- evaluate the progress of the maturing field of visualization,
- help focus and direct future research projects, and
- provide guidance on how to apportion national resources as research challenges change rapidly in the fast-paced world of information technology.

We explore the state of the field, examine the potential impact of visualization on areas of national and international importance, and present our findings and recommendations for the future of our growing discipline. Our audience is twofold: the supporters, sponsors, and application users of visualization research on the one hand, and researchers and practitioners in visualization on the other. We direct our discussion toward solving key problems of national interest and helping this work's sponsors to concentrate resources to the greatest effect. Our findings and recommendations reflect information gathered from visualization and applications scientists during two workshops on VRC, as well as input from the larger visualization community.

The value of visualization

Advances in the science and technology of computing have engendered unprecedented improvements in scientific, biomedical, and engineering research; defense and national security; and industrial innovation. Continuing and accelerating these advancements will require people to comprehend vast amounts of data and information produced from a multitude of sources.[3] Visualization, namely helping people explore or explain data through software systems that provide a static or interactive visual representation, will be critical in achieving this goal. Visualization designers exploit the high-bandwidth channel of human visual perception to help people comprehend information orders of magnitude more quickly than through reading raw numbers or text.

Visualization is fundamental to understanding models of complex phenomena, such as multilevel models of human physiology from DNA to whole organs, multicentury climate shifts, international financial markets, or multidimensional simulations of airflow past a jet wing. Visualization reduces and refines data streams, thus enabling us to winnow huge volumes of data in applications such as public health surveillance at a regional or national level to track the spread of infectious diseases. Visualizations of such application problems as hurricane dynamics and biomedical imaging are generating new knowledge that crosses traditional disciplinary boundaries. Visualization can provide industry with a competitive edge by transforming business and engineering practices.

Although well-designed visualizations have the power to help people enormously, naive visualization attempts are all too often ineffective or even actively misleading. Designing effective visualizations is a complex process that requires a sophisticated understanding of human information-processing capabilities, both visual and cognitive, and a solid grounding in the considerable, already existing body of work in the visualization field. Further research in visualization—and the technology transfer of effective visualization methodologies into the working practice of medicine, science, engineering, and business—will be critical in handling the ongoing information explosion. The insights provided through visualization will help specialists discover or create new theories, techniques, and methods, and improve the daily lives of the general public.

While visualization is itself a discipline, advances in visualization lead inevitably to advances in other disciplines. Just as knowledge of mathematics and statistics has become indispensable in subjects as diverse as the traditional sciences, economics, security, medicine, sociology, and public policy, so too is visualization becoming indispensable in enabling researchers in other fields to achieve their goals. Like statistics, visualization is concerned with the analysis and interpretation of information, both quantitative and qualitative, and with the presentation of data in a way that conveys their salient features most clearly. Both fields develop, understand,

 Published by the IEEE Computer Society

and abstract data-analytic ideas and package them in the form of techniques, algorithms, and software for a multitude of application areas.

However, despite the importance of visualization to discovery, security, and competitiveness, support for research and development in this critical, multidisciplinary field has been inadequate. Unless we recommit ourselves to substantial support for visualization research, development, and technology transfer, we will see a decline in the progress of discovery in other important disciplines dependent on visualization. As these disciplines lose their ability to harness and make sense of information, the rate of discovery itself will decline. In the inevitable chain reaction, we will lose our competitive edge in business and industry.

Findings

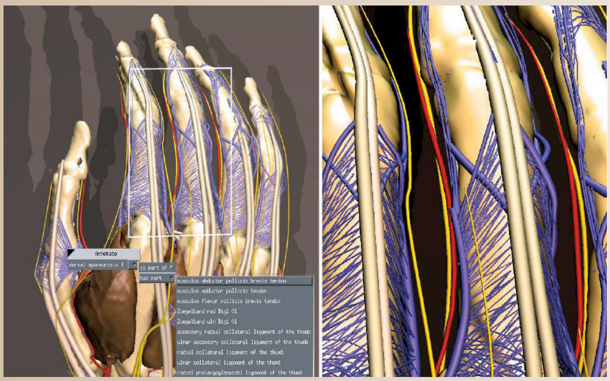
Visualization is indispensable to the solution of complex problems in every sector, from traditional medical, science, and engineering domains to such key areas as financial markets, national security, and public health. Advances in visualization enable researchers to analyze and understand unprecedented amounts of experimental, simulated, and observational data and through this understanding to address problems previously deemed intractable or beyond imagination. Yet, despite the great opportunities created by and needs fulfilled by visualization, the NSF and NIH (and other US government agencies) have not effectively recognized the strategic significance and importance of visualization in either their organizational structures or their research and educational planning. The recent and cogent book outlining the visual analytics research agenda,[4] which dovetails closely with visualization, offers promise that visualization for the national security application area will be well funded in the near future. However, that effort encompasses only one sector and is short term, whereas the field needs long-term support across many sectors. The current distribution of funding sources does not reflect the potential benefits of visualization research to specific application areas. These inadequacies compromise the future of US scientific leadership, public health, and economic competitiveness.

Many important challenges in visualization will not be solved by simply waiting for computers to get faster, or by refining existing algorithms. Visualization researchers should collaborate closely with domain experts who have appropriate driving tasks in data-rich fields to produce tools and techniques that solve clear real-world needs. Visualization researchers also need to integrate with and be informed by methodologies in many other fields—including statistics, data mining, and cognitive psychology—to facilitate analysis from both qualitative and quantitative perspectives. Examining how and why visualizations work will require a deep understanding of human characteristics, strengths, and limitations. The set of current visualization techniques is rich and powerful, but far from complete; we need to systematically explore the design space of possible visual representations. Designing appropriate interaction metaphors for current and future hardware will be crucial for harnessing the full power of visualization systems.

Evaluating the extent to which proposed visualization techniques solve problems grounded in real-world tasks is critical to the success of our field. Quantitative evaluation methods include measurement of algorithm execution times and memory performance, and formal user studies in a laboratory setting aimed at generating statistically significant results measuring user performance on abstracted tasks using metrics such as task completion times or error rates. Qualitative evaluation approaches include anecdotal evidence of discoveries by real-world users, adoption rates based on user-community size, and qualitative user studies ranging from ethnographic analysis of target-user work practices to longitudinal field studies to informal usability evaluation of a prototype system. Finally, evaluative analysis with careful justification of design choices with respect to conceptual and theoretical frameworks underlying

Teaching Anatomy and Planning Surgery

Detailed anatomic models of delicate organs such as the human hand are a prerequisite for both teaching the complex anatomy and the preoperative simulation of interventions. While classical anatomy atlases can provide sufficient anatomical detail in a set of static images, they do not allow choosing user-defined views or performing surgical interaction. The picture and inset in Figure A illustrates Voxel-Man/Upper Limb, a novel computer-based anatomy model that not only allows arbitrary viewing and dissection, but also the interrogation of the anatomic constituents by mouse click. The pictorial model was created from the Visible Human Project data set using a combination of volume visualization for bone and muscles, and surface modeling for blood vessels, nerves, ligaments, and tendons.[1] The pictorial model is linked to a knowledge base, describing the anatomic constituents and their relations. Voxel-Man supports a range of practitioners, from medical students to expert surgeons, in coping with the complexity of state-of-the-art microsurgical interventions. A future challenge will be to extend the knowledge base so that the system can warn the user of consequences of a surgical interaction for the patient.



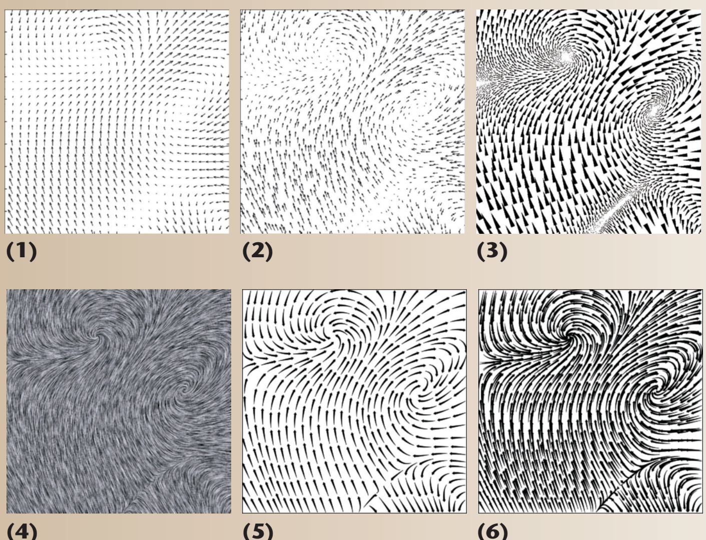
A View of Voxel-Man/Upper Limb. (Reprinted with permission of Wiley-Liss. a subsidiary of John Wiley & Sons.)

Reference

1. S. Gehrmann et al., "A Novel Interactive Anatomic Atlas of the Hand," *Clinical Anatomy*, DOI 10.1002/ca.20266, 2006.

Characterizing Flow Visualization Methods

For decades, researchers have been developing visualization techniques that advance the state of the art and are published in peer-reviewed journals. However, there are disproportionately few quantitative studies comparing visualization techniques, such as the characterization in Figure A of the differences between flow visualization methods—showing six methods for visualizing the same 2D vector field.[1] Subjects who participated in the user study performed several tasks including identifying the type and location of critical points in visualizations. Assuming roughly equal importance for all tasks, the streamline visualization shown in Figure A6 performed best overall: on average, subjects were fastest and most accurate when using it.



A A comparison of six methods for visualizing the same 2D vector field: (1) icons on a regular grid, (2) icons on a jittered grid, (3) layering method inspired by oil painting, (4) line-integral convolution, (5) image-guided streamlines, (6) streamlines seeded on a regular grid. (Courtesy of David Laidlaw, Brown University.)

This study produced both quantitative results and a basis for comparing other visualization methods, for creating more effective methods, and for defining additional tasks to further understand tradeoffs among methods. A future challenge is to develop evaluation methods for more complex 3D time-varying flows.

Reference

1. D.H. Laidlaw et al., "Comparing 2D Vector Field Visualization Methods: A User Study," *IEEE Trans. Visualization and Computer Graphics*, vol. 11, no. 1, 2005, pp. 59-70.

the visualization field is useful both for understanding why and how a method works, and for extending the frameworks themselves.

One of the basic requirements of science is that experiments be repeatable. There is great need for sustained and methodical creation and maintenance of curated data, model, and task repositories so that visualization researchers can benchmark new algorithms and techniques by comparing them directly to the results of previous work. Although visualization practitioners are typically not the primary source of the data themselves, they should be advocates for open science through data sharing whenever possible.

In visualization, as in other research areas, research can be divided into the three categories of basic or foundational work, transitional approaches to create and refine techniques, and application-driven efforts. Although transitional research is at the heart of any field, in some areas of visualization a disproportionate amount of attention is currently devoted to incremental refinement of a narrow set of techniques. Cycles of interaction between all three of these areas must occur to keep the field of visualization vibrant, driven by applied problems and grounded in foundational research. Moreover, just as being engaged with domain scientists will help visualization research become more effective, being engaged with visualization researchers will help domain scientists by providing them with access to state-of-the-art tools. These collaborations will support grass-roots technology transfer of visualization methodologies into application domains in the economic, scientific, and public service sectors.

Revisiting the hardware, software, and networking issues discussed in the 1987 report reveals the enormous progress made in the past decades. Fast and cheap commodity hardware meets most of the CPU and graphics needs of visualization today. The current availability of commercial volume-rendering hardware is a success story for the field. Exciting new advances in display hardware will have a major impact on visualization. Advances in networking will greatly facilitate collaboration and other remote visualization opportunities. Both commercial and open source visualization software systems are thriving as the field matures. The open source model offers many benefits to both academia and industry, and to both researchers and end users.

Recommendations

We explored these findings with the assistance of area experts in two separate workshops. Based on the deliberations of our panelists, we make the following recommendations.

Principal agency leadership recommendation

NSF and NIH must make coordinated investments in visualization to address the 21st century's most important problems, which are predominantly collaborative, crossing disciplines, agencies, and sectors. Both NSF and NIH can and should provide leadership to other federal funding partners and to the research communities they support. To achieve this, NSF and NIH should modify their programmatic practices to better engage visualization capabilities across disciplines important to scientific and social progress and to encourage and reward interdisciplinary research, open practices, and reproducibility in technical and scientific developments. Such agency leadership is critical if we are to meet US needs in critical areas and to maintain US competitiveness in a global environment.

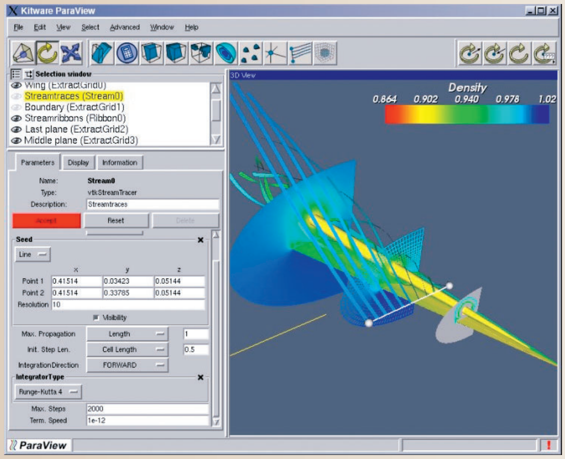
The Visualization Toolkit

In 1993, three visualization researchers from the General Electric corporate R&D center began to develop an open source visualization system. This system, which came to be known as the Visualization Toolkit (VTK), was initially envisioned as a teaching and research collaboration tool, hence its release under an open source license. The software gained rapid acceptance, in part due to the sophistication of its object-oriented design and software process, but also because of the community of users that formed around it. VTK is now in worldwide use, and has helped spawn several small companies and derivative products. For example, Kitware, Inc. was formed in 1998 to support VTK, subsequently creating products based on the toolkit including the open source ParaView parallel visualization system and the proprietary VolView volume-rendering application.[1] VTK continues to evolve with contributions from researchers in academia, US national laboratories, and businesses, and is used in dozens of commercial software applications.

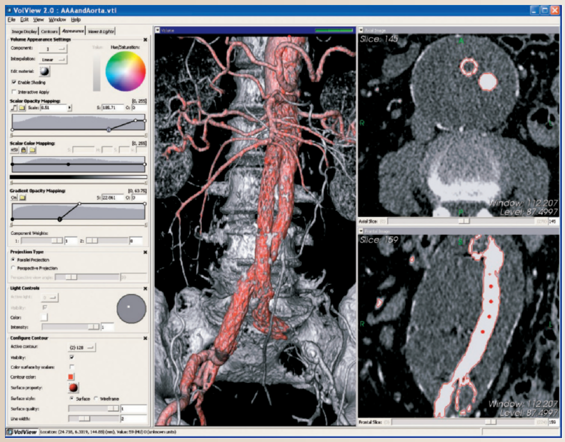
Figure A shows a computational fluid dynamics visualization using ParaView (Figure A1) and volume rendering using VolView (Figure A2). Figure A3 uses the LOx Post data set, simulating the flow of liquid oxygen across a flat plate with a cylindrical post perpendicular to the flow. This model studies the flow in a rocket engine, where the post promotes the mixing of the liquid oxygen.[2]

References

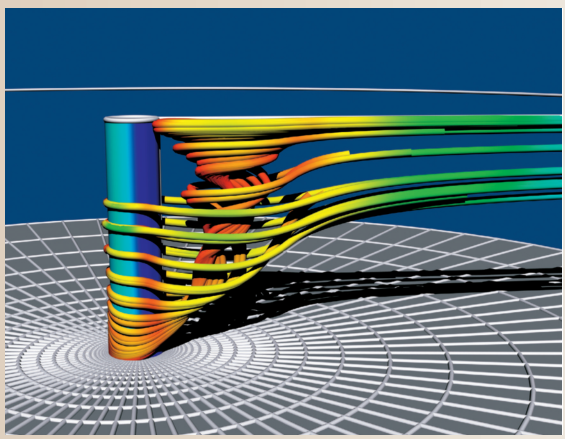
1. W.J. Schroeder, K. Martin, and B. Lorensen, *The Visualization Toolkit: An Object Oriented Approach to Computer Graphics*, 3rd ed., Kitware, Inc., 2004.
2. S.E. Rogers, D. Kwak, and U.K. Kaul, "A Numerical Study of Three-Dimensional Incompressible Flow around Multiple Posts," *Proc. AIAA Aerospace Sciences Conf.*, AIAA paper 86-0353, 1986, pp. 1-12.



(1)



(2)



(3)

A Sample visualizations from publicly available visualization software: (1) ParaView, (2) VolView, and (3) VTK. (Courtesy of Kitware Inc.)

Short-term policy recommendation

Policy changes for both funding and publication review to encourage evaluation of visualization and collaboration between visualization and other fields can be implemented immediately, without requiring new funding initiatives. Within visualization, review protocols should reflect the importance of evaluation to determine the success and characterize the suitability of techniques. Methodological rigor should be expected when user studies are proposed or reviewed, and as necessary, visualization researchers should collaborate with those trained in fields such as human–computer interaction, psychology, and statistics. Peer review of proposals and publications should also reward visualization driven by real-world data and tasks, in close collaboration with target users. In other fields, review protocols should encourage domain scientists who create partnerships with visualization researchers, just as engagement with statisticians is considered normal practice in many areas such as biomedical research.

Midterm direction recommendation

Pilot programs should be established to combine efforts and create collaborative development between visualization and other research domains. Funding for such programs should contribute proportionately to both the visualization research and the domain specialty. The purpose of this effort will be to improve the penetration of emerging technologies into new domains, increasing their facility to move data and share results through visualization. All of the awards in this area should be dedicated to open access of source code, availability of research data to the worldwide community, and reproducibility of the technical and scientific developments.

Long-term investment recommendation

We recommend a coordinated and sustained national investment in a spectrum of centralized and distributed research programs to promote foundational, transitional, and applied visualization research in support of science, medicine, business, and other socially important concerns. This investment is critical for the US to remain competitive in a global research and development community that has increasing resources. In addition to funding transitional research, such programs should emphasize foundational research and integration of methodologies from other fields, and collaboration with domain specialists who provide driving problems in areas of national concern. A long-term funding commitment is required for the creation and maintenance of curated data collections, and open source software, to promote open science. Characterizing how and why visualizations work, systematically exploring the design space of visual representations, developing new interaction approaches, and exploiting the possibilities of novel display hardware will be particularly important areas of emphasis. ■

Acknowledgments

We are indebted to the expert and visionary VRC workshop panelists for sharing their considerable talents and insights, and to NIH and NSF for their sponsorship. In particular, we thank panelists Maneesh Agrawala, Liz Bullitt, Steve Cutchin, David Ebert, Thomas Ertl, Steve Feiner, Felice Frankel, Bob Galloway, Alyssa Goodman, Mike Halle, Pat Hanrahan, Chuck Hansen, Helwig Hauser, Karl Heinz Höhne, Ken Joy, Arie Kaufman, Daniel Keim, David Laidlaw, Ming Lin, Leslie Loew, Bill Lorensen, Wayne Loschen, Patrick Lynch, Kwan-Liu Ma, Alan MacEachren, Chris North, Art Olson, Catherine Plaisant, Jerry Prince, Will Schroeder, Jack Snoeyink, John Stasko, Barbara Tversky, Matthew O. Ward, Colin Ware, Ross Whitaker, Turner Whitted, and Jarke van Wijk.

References

1. B.H. McCormick, T.A. DeFanti, and M.D. Brown, *Visualization in Scientific Computing*, National Science Foundation, 1987.
2. C. Johnson et al., *NIH-NSF Visualization Research Challenges Report*, IEEE Press, 2006.
3. P. Lyman and H.R. Varian, *How Much Information*, 2003; http://www.sims.berkeley.edu/how-much-info-2003.
4. J.J. Thomas and K.A. Cook, eds., *Illuminating the Path: The Research and Development Agenda for Visual Analytics*, National Visualization and Analytics Center, 2005.

Contact Terry Yoo at tyoo@mail.nih.gov.

Contact editor Theresa-Marie Rhyne at tmrhyne@ncsu.edu.