FY2009 Final Report

NSF ITR Cooperative Agreement OCI-0225642

October 1, 2008 – September 30, 2009

SUBMITTED October 30, 2009

Larry Smarr, Principal Investigator
California Institute for Telecommunications and Information Technology (Calit2)
University of California, San Diego
smarr@cs.ucsd.edu
www.optiputer.net

Table of Contents

1. OptIPuter Participants

1.A. Primary Personnel

Name	Project Role(s)	>160 Hours/Yr during project
Larry Smarr	Principal Investigator	Yes
Thomas A. DeFanti	Co-Principal Investigator	Yes
Mark Ellisman	Co-Principal Investigator	Yes
Jason Leigh	Co-Principal Investigator	Yes
Philip Papadopoulos	Co-Principal Investigator	Yes

1.B. Other Senior Personnel 2009

University of California San Diego (UCSD)		
Name	**Project Role(s)**	**>160 Hours/Yr during project**
Joe Keefe	Other Personnel	Yes

University of Illinois at Chicago (UIC)		
Name	**Project Role(s)**	**>160 Hours/Yr during project**
Maxine Brown	Senior Personnel	Yes
Luc Renambot	Senior Personnel	Yes
Alan Verlo	Senior Personnel	Yes
Ratko Jagodic	Graduate Student	Yes
Byungil Jeong	Graduate Student	Yes
Venkatram Vishwanath	Graduate Student	Yes

1.C. Other Partner Organizations

BigBangwidth <www.bigbangwidth.com> is the developer of the Lightpath Accelerator(TM), which automatically brings up to 10Gbps connections directly to high-performance devices by providing light paths between network hosts, such as workstations and servers, which are otherwise connected through a packet network. OptIPuter partner Chien worked with them to evaluate it, and explored different ways to integrate it into the OptIPuter infrastructure.

Calient Networks <www.calient.net> is the developer of the DiamondWave(TM) Photonic 3D MEMS (Micro-Electro-Mechanical Systems) Switch used by OptIPuter teams. OptIPuter partner UIC/EVL purchased a 128-port Calient, located in Chicago (at StarLight), and a 64-port Calient, located in Amsterdam (at NetherLight), to switch lambdas.

CANARIE, the Canadian Network of the Advancement of Research, Industry and Education <www.canarie.ca/about/index.html> is working with the OptIPuter's optical backplane group to explore application of its User Controlled Light Path (UCLP) software. Bill St. Arnaud, network director, has participated in OptIPuter backplane meetings.

Chiaro Networks <www.chiaro.com> was an OptIPuter industrial partner, but the company went out of business in 2005. Steve Wallach, former Vice President of Technology, is a member of the OptIPuter Frontier Advisory Board.

Communications Research Centre (CRC), Canada <www.crc.ca> is an OptIPuter affiliate partner, interested in incorporating UCLPv2 into the OptIPuter infrastructure, determining if Visual Networking software associated with IBM's DCV can be made to work with SAGE, and porting Carlton University's Participatory Design Studio (PDS) application to the OptIPuter environment. CRC is the Canadian federal government's Centre of Excellence for R&D in advanced telecommunications and is an agency of Industry Canada with over 220 research staff located in Ottawa, Ontario, Canada.

Glimmerglass Networks <www.glimmerglassnet.com> is the developer of the Reflexion(TM) 3D MEMS switch with a photonic multicasting option. OptIPuter partner UIC/EVL worked with Glimmerglass to develop the photonic

multicast option. When combined with proper scheduling of cluster computing resources and light paths, this architecture allows applications to create multiple, simultaneous, distributed computing pipelines.

IBM <www.ibm.com> is an OptIPuter industrial partner. Alan Benner, a senior member of the IBM Systems Architecture and Performance Team within the IBM eServer group, participates in the OptIPuter project and is a member of the OptIPuter Frontier Advisory Board. IBM works with the UCSD National Center for Microscopy and Imaging Research (NCMIR) to utilize its T221 9-megapixel display for interactively visualizing large montage brain microscopy images. In 2003, the OptIPuter project acquired a 10-node graphics-intensive cluster, plus an experimental IBM Scalable Graphics Engine, and two more T221s for the Earth Sciences application work at UCSD Scripps Institution of Oceanography. In 2004, the OptIPuter project (Smarr, PI) submitted a proposal to the IBM Shared University Research (SUR) program and received a storage-intensive cluster.

KISTI, the Korea Institute of Science and Technology Information
<www.kisti.re.kr/kisti/english/index_english.jsp> is an OptIPuter international affiliate partner working on advanced visualization tools and techniques.

Lucent Technologies <www.lucent.com> is a partner in an NSF MRI proposal, called "Quartzite" (Papadopoulos, PI), and provided the project with a novel Wavelength-Selective switch (WS-Switch), not yet commercially available. The OptIPuter assumes a bandwidth-rich world; Quartzite research assumes that campus backbone fiber carries multiple "stand-by" allocatable wavelengths (lambdas) in addition to the common shared and routed Internet traffic, which can be made available to data-intensive applications for on-demand capacity provisioning.

NASA <http://www1.nasa.gov/home> sites NASA Ames Research Center, NASA Goddard Space Flight Center and Jet Propulsion Laboratory are OptIPuter affiliate partners. NASA Goddard connected to National LambdaRail and CAVEwave in order to do data-intensive Earth Science experiments with OptIPuter partner UCSD Scripps Institution of Oceanography (SIO). NASA Goddard now works with UIC/EVL to adapt OptIPuter technologies to speed up supercomputer computations of weather forecasting simulations.

National Insitute of Advanced Industrial Science and Technology (AIST) of Japan's Grid Technology Research Center (GTRC) <http://www.gtrc.aist.go.jp/en/> is an OptIPuter international affiliate partner working on advanced visualization tools and techniques.

Purdue University's Envision Center for Data Perceptualization and Rosen Center for Advanced Computing <www.envision.purdue.edu> is an OptIPuter affiliate partner, involved with advanced visualization tools and techniques.

Rincon Research Corporation <www.rincon.com> is an OptIPuter industrial partner. Rincon innovates, develops, and fields digital signal processing (DSP) products and services for the United States Defense and Intelligence communities in defense of national security, and works with Calit2 and the OptIPuter project on advanced visualization tools and techniques.

SARA Computing & Networking Services <http://www.sara.nl> is an OptIPuter international affiliate partner, bringing optical networking and visualization expertise to the OptIPuter. SARA hosts the SURFnet NetherLight facility, the sister facility to StarLight in Chicago. Together with UvA, they manage the Lighthouse network and computer research testbed.

Sun Microsystems <www.sun.com> is working closely with UCSD to develop an OptIPuter compute cluster. In 2003, Sun donated a 128-node compute-intensive cluster for the UCSD OptIPuter testbed.

Telcordia Technologies, Inc. <www.telcordia.com> is an OptIPuter industrial partner. George Clapp, a senior member of the Telcordia Applied Research Team and an expert in optical control plane and networking for lambda networks, is the SAIC technical project manager for the OptIPuter and a member of the OptIPuter Frontier Advisory Board. In past years, he has spent up to 50% time on the OptIPuter project.

University of Amsterdam (UvA) Systems and Networking Engineering Research Group <www.science.uva.nl/research/sne> is the OptIPuter's first international affiliate partner, working with UIC

colleagues to develop an optically switched OptIPuter node, connecting through StarLight.

University of Michigan (School of Information <www.si.umich.edu> and Collaboratory for Research on Electronic Work <www.crew.umich.edu>) is an OptIPuter affiliate partner working on incorporating social science requirements analysis and collaboration tools (e.g., HD video teleconferencing) into UIC/EVL advanced visualization tools and techniques.

US Geological Survey (USGS) National Center for Earth Resources Observation and Science (EROS) <http://eros.usgs.gov/> archives data from land remote sensing satellite missions and conducts research in applications of this data as well. As an affiliate OptIPuter partner, USGS EROS works with team members on application, technology transfer and outreach activities. Brian Davis is the USGS liaison to the OptIPuter team.

1.D. Other Collaborators and Contacts

CENIC <www.cenic.org>, the Corporation for Education Network Initiatives in California, provides the OptIPuter project team with either CalREN-HPR or National LambdaRail (NLR) networking, to enable participating universities in Southern California to connect to one another, as well as team sites in Chicago.

Cisco Systems Inc. <www.cisco.com> supports the extension of the OptIPuter to digital cinema through the CineGrid project. A substantial part of this support is in the form of a gift. Cisco has also provided 30Gb of layer 2 network access on the National LambdaRail from California to Washington to Illinois and to Washington D.C., including 10GE equipped 6506 switches.

Centro de Investigación Cientifica y de Educación Superior de Ensenada (CICESE) <www.cicese.mx> in Baja California, Mexico, is a "sister" research facility to Scripps Institution of Oceanography. CUDI, the Mexican Research & Education network, worked with CENIC to put a 10Gbps link between UCSD/SIO and CICESE so they can have become an OptIPuter partner.

JVC America <www.jvc.com> has been testing 4K projectors with Calit2/CRCA. These 4K devices can be straightforwardly implemented as OptIPortals since they are all driven by 4 DVI inputs. Prototype working systems were shown at Calit2 during SIGGRAPH 07 (August 3-9, 2007) and will be further developed for SC'07.

National LambdaRail (NLR) <www.nlr.net> is a major initiative of US research universities and private sector technology companies to provide a national-scale infrastructure for research and experimentation in networking technologies and applications. CEO Tom West has been supportive of donating some bandwidth to the OptIPuter project (~1Gbps) between Chicago and San Diego.

San Diego Telecom Council <www.sdtelecom.org>, a 300-member Southern California telecom council, strongly endorses the OptIPuter efforts. Co-founder Franz Birkner is a member of the OptIPuter Frontier Advisory Board. In 2005, the organization changed its name to CommNexus San Diego.

Sharp Laboratories of America <www.sharplabs.com> supports EVL and Calit2 to develop an OptIPortal using Sharp HDTV displays. In addtion, EVL is working with Sharp to procure and test 4K LCD panels; this was demonstrated at SC08.

Toshiba <www.toshiba.com> loaned Calit2/CRCA a 4K prototype LCD panel that was shown at Calit2 during SIGGRAPH 07 (August 3-9, 2007), driven by four Playstation3s.

2. OptIPuter Activities and Findings

2.A. Research Activities

2.A.1. OptIPuter Accomplishments

On March 23, 2009, UCSD requested a no-cost extension for the OptIPuter award through September 30, 2009. This no-cost extension was recommended by our NSF program officers but, we recently learned, was subsequently turned down by the NSF Division of Grants and Agreements (DGA). Though OptIPuter had expended all its funding, lead institutions UCSD/Calit2 and UIC/EVL requested the no-cost extension to continue to support the nascent OptIPlanet Collaboratory, to better comprehend and report on the implications of OptIPuter, and to analyze user requirements for high-performance networks that connect instruments, computers and data stores with end-system tiled display walls (a.k.a. OptIPortals). We felt that a no-cost extension would enable OptIPuter principals to do a forward-looking analysis of advanced cyberinfrastructure to benefit the Nation's science and engineering communities.

The OptIPuter's NSF Cooperative Agreement defines its mission as "…enabling collaborating scientists to interactively explore massive amounts of previously uncorrelated data by developing a radical new architecture for a number of this decade's e-Science shared information technology facilities." Further, the Agreement states that "the OptIPuter will be used by new application scientists outside the initial cohort of project investigators."

The OptIPuter has proven to be an extremely successful and high-profile NSF project that has attracted, and continues to attract, major interest from a number of e-science disciplines. The *OptIPuter FY2008 Annual Report,* available on the OptIPuter website <www.optiputer.net/publications/reports/OptIPuter-2007PPP-DISTRIBUTION-COPY-021508.pdf>, documents the project's many accomplishments:

- A unique systems architecture (OptIPortals and SAGE) to enable interactive access to remote gigabyte visualization data objects.
- The development of new grid-computing paradigms – data and visualization techniques, middleware, transport protocols and optical signaling, control and management software that enable applications to dynamically manage lambda resources just as they do any grid resource – which are documented in 13 papers in a special section of the journal *Future Generation Computer Systems (FGCS)/ The International Journal of Grid Computing: Theory, Methods & Applications*, entitled "OptIPlanet: The OptIPuter Global Collaboratory," Volume 25, Issue 2, Elsevier, February 2009, pp. 109-197.
- The creation of a nascent OptIPlanet Collaboratory – representing almost 60 sites worldwide and a variety of application disciplines – that wishes to acquire and/or contribute to OptIPuter-developed tools and techniques.
- The development of web-based documentation that explains how to build tiled display walls and how to obtain open-source software.

The OptIPuter principals felt that it was in our interest, and NSF's interest, to better understand the OptIPuter phenomenon, to better help users who are early adaptors to ensure success, to analyze user requirements for advanced cyberinfrastructure, and to document next steps.

Over the past year, OptIPuter lead institutions UCSD/Calit2 and UIC/EVL hardened existing software, documented OptIPuter hardware, software and networking requirements, and deployed and trained new user communities. In addition, EVL polled the OptIPlanet's SAGE community about what capabilities and enhancements they would like to see in SAGE, and used this information as the basis of a three-year roadmap submitted as part of an NSF STCI proposal to fund SAGE's development and deployment. The OptIPlanet Collaboratory, which currently totals about 60 sites worldwide, is adopting, enhancing and contributing to this evolving cyberinfrastructure to support global communities who collaborate on complex environmental, biomedical, physical and homeland security problems.

2.A.2. OptIPuter Documentation

Calit2 maintains documentation for those building an OptIPortal system running Rocks/SAGE and/or CGLX at <http://wiki.optiputer.net/optiportal>. CGLX (Cross-Platform Cluster Graphic Library), an alternative to SAGE, is an OpenGL-based graphics framework developed by Falko Kuester at UCSD/Calit2 <http://vis.ucsd.edu/~cglx>. Feasibility studies to integrate CGLX with SAGE have been performed, enabling high-performance, interactive 3D visualization and display (via CGLX) and pervasive streaming and distribution (via SAGE).

For groups who have sophisticated graphics requirements and have tailored their OptIPortal visualization clusters to

maximize rendering and/or streaming, SAGE can be run without Rocks. SAGE documentation is available online <www.evl.uic.edu/cavern/sage>.

2.A.3. OptIPuter Deployment and Training

OptIPortals continue to be deployed worldwide, interconnected by global optical networks, creating a nascent *OptIPlanet Collaboratory*. Both Calit2 and EVL continue to consult with new user communities as best they can, even though OptIPuter funds have been spent. Notably, the newest member of the OptIPlanet Collaboratory is KAUST, the King Abdullah University for Science and Technology, a new university in Saudi Arabia. KAUST currently funds Calit2 and EVL to develop and deploy the latest visualization technologies to its new Showcase area (see Section 2.B.1.2 for further information), and to collaborate on joint research opportunities using these unique resources.

2.A.4. SAGE, the Scalable Adaptive Graphics Environment

The OptIPuter team developed and deployed prototypes of scalable *personal computers,* or OptIPortals. An OptIPortal is a tiled display wall driven by a computer cluster interconnected with Gigabit/s or 10 Gigabit/s Ethernet. Also required is a globally connected and well-integrated *operating environment* to facilitate data sharing and analysis. SAGE provides such an integrated work environment.

SAGE and OptIPortals enable the creation of *cyber-mashups,* or juxtapositions, of information, which is a critical component of data analysis. Just as today, one creates mashups of data types using windows on a laptop, scientists can use SAGE to access, display and share a variety of data-intensive information, in a variety of resolutions and formats, from multiple sources, to create cyber-mashups on OptIPortals. This, in turn, helps scientists gain more holistic views and insight regarding complex issues, and make more informed observations and discoveries.

SAGE is cross-platform, open-source middleware that enables users worldwide to have a common operating environment, or framework, to access, stream and juxtapose data objects – whether digital cinema animations, high-resolution images, high-definition video-teleconferencing, presentation slides, documents, spreadsheets or laptop screens – on one or more OptIPortals.

During the past year of this OptIPuter award, EVL submitted an NSF STCI proposal for the "OptIPlanet Cyber-Mashup," which was awarded. In writing the proposal, EVL polled the OptIPlanet's SAGE community about what capabilities and enhancements they would like to see in SAGE. User responses were overwhelmingly supportive, and helped define a 3-year roadmap. Four major areas were identified: authoring, editing and interaction, streaming and collaboration. These findings are further explained in Section 2.B.2.

As an example of the impact that the OptIPuter project has had on its collaborators, we quote here from a letter written by Dr. Shinji Shimojo in support of the NSF STCI "OptIPlanet Cyber-Mashup" proposal. Dr. Shimojo was formerly director of the CyberMedia Center at Osaka University in Japan, and is now director of JGN2plus (Japan's 10Gbps national and international testbed network) at the National Institute of Information and Communications Technology (NICT):

I am a Director of JGN2plus at NICT, Japan. JGN2plus is a nationwide testbed network for R&D for new-generation networks. We provide the infrastructure to the researchers as well as promote R&E for new-generation networks through the use of the testbed.

When I was a member of CyberMedia Center, Osaka University, one of seven national high-performance computer centers, I was promoting visualization in the HPC area. So, we built a CAVE and Tiled Display Wall in our center. Through this activity, I have known Dr. Jason Leigh and OptIPuter project since 2005. We have been users of SAGE since 2005 in practical use as well as in research. We admire its portability, usefulness and extensibility. After I moved to NICT last year, we promoted the use of SAGE and OptIPortals on JGN2plus because it could be a future platform that we could use to enjoy the benefits of both high-speed networking and its advanced use of parallel computing. OpIPortals equipped with SAGE could show HD or even 4K streaming data, large volumes of 3D data through the use of advanced parallel rendering algorithms, and ultra-fine-grain image data through the use of parallel data retrieval. We installed at least four Tiled Display Walls connected to JGN2plus. We fund one research group who is developing parallel volume rendering of large-scale data using SAGE. We initiated a research project for building an interactive platform for digital museums. By using the OptIPortal, any museum can have a platform to share its precious preserved material in any kind of format. Both projects are ongoing for larger communities.

It should also be noted that the EVL student who developed SAGE, Byungil Jeong, now works for the Texas Advanced Computing Center (TACC), a SAGE user. About a year ago, TACC built the largest OptIPortal in the world, the 307-Megapixel Stallion display. Jeong, as part of his TACC duties, continues to work on SAGE development with EVL because TACC sees merit in its capabilities. TACC also supported EVL's STCI proposal.

2.A.5. LambdaRAM

EVL's LambdaRAM development, initially funded by OptIPuter (with subsequent funding from NASA), has matured and proven invaluable to weather prediction calculations done by NASA Goddard Space Flight Center (GSFC), an early OptIPuter affiliate partner. Details were provided in the *OptIPuter FY2008 Annual Report.* In the past year, EVL graduate student Venkat Vishwanath defended his PhD dissertation, *LambdaRAM: A high-performance, multi-dimensional, distributed cache for data-intensive applications over high-speed networks.*

Vishwanath subsequently received an Argonne National Laboratory Director's Fellowship and is currently a Postdoc in Argonne's Mathematics and Computer Science (MCS) Directorate. He plans to focus on the area of "data coupling" using the Argonne Leadership Computing Facility (ALCF) petascale computer, building on his research with LambdaRAM.

2.A.6. Meetings, Presentations, Conference Participation

During the entire reporting period, Calit2 had visitors to see Falko Kuester's HiPerSpace OptIPortal virtually everyday of the week, sometimes several tours per day. These visits often involved live HD linkups between the NASA Ames Lunar Science Institute OptIPortal, designed with the help of Calit2, and the Calit2 OptIPortal over a CENIC 10Gbps optical link.

September 16-25, 2009. Tom DeFanti traveled to Saudi Arabia for the opening of KAUST.

September 15, 2009. Jonathan Abon, manager of Market Strategy at Tellabs in Illinois, visited EVL to learn more about OptIPortals and SAGE. He had seen a press release on EVL's receiving an NSF STCI award to continue SAGE development, and wanted to learn more about the demands of multi-gigabit networking.

September 14, 2009. Alan Verlo attended the CyberSecurity Summit 2009 for Large Research Facilities, sponsored by EDUCAUSE in Arlington, VA.

August 20, 2009. Larry Smarr gave the presentation "Universities as 'Smart Cities' in a Globally Connected World – How Will They be Transformed?" at the conference RE-INVENT to RE-POSITION – TRANSFORMED BY ICT, held at Monash University, Melbourne, Australia.

August 19, 2009. Larry Smarr gave the presentation "Global Cyberinfrastructure to Support e-Research" at the conference e-XPO: e-Research@Monash**,** held at Monash University, Melbourne, Australia.

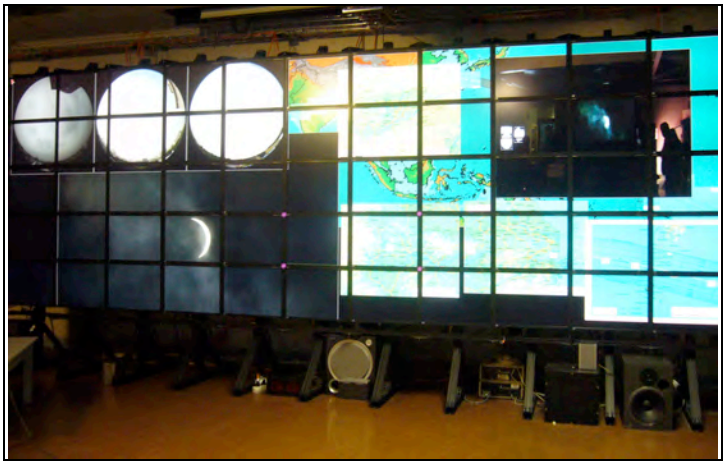
August 11-September 15, 2009. Calit2 and EVL staff traveled to Saudi Arabia to help set up the KAUST Visualization Showcase area.

August 10, 2009. EVL's newest OptIPortal, built from NEC almost seamless tiled displays, is part of EVL's Cyber-Commons room, a high-tech classroom and meeting space. In August, Cyber-Commons was used for a one-week *Many-Core Processors* course developed by the Virtual School of Computational Science and Engineering of the Great Lakes Consortium for Petascale Computation (GLCPC), as shown in this photo. A weeklong seminar was streamed from University of Illinois at Urbana-Champaign's National Center for Supercomputing Applications to EVL in Chicago <www.evl.uic.edu/cavern/EVL-GLCPC/GLCPC_Summer_School.html>.

July 29, 2009. Nirav Merchant of University of Arizona, who has an NSF-funded iPlant Collaborative project <www.iplantcollaborative.org>, was in Chicago for a "Genotype to Phenotype" workshop, and visited EVL with several key iPlant members to learn more about applying OptIPuter technologies to plant biology.

July 29, 2009. Chicago's Adler Planetarium, which has OptIPuter technologies as part of its Space Visualization Laboratory, brought Jonathan Fay of Microsoft Research, the primary developer of the World Wide Telescope project, to EVL for demos and tours.

July 22, 2009. Larry Smarr gave the invited talk "The OptIPuter and Its Applications" at the IEEE/LEOS Summer 2009 Topicals Meeting on Future Global Networks, Newport Beach, CA.



July 22-23, 2009. EVL hosted a meeting of the ON*VECTOR Terabit LAN Workshop at UIC in Chicago. This is a group of researchers from NTT Network Innovation Laboratories, Keio University, University of Tokyo, UCSD/Calit2 and UIC/EVL. Of special note was that there was a total solar eclipse on July 22, 2009 that was only visible from a narrow corridor through northern India, eastern Nepal, northern Bangladesh, Bhutan, the northern tip of Myanmar, central China and the Pacific Ocean. Researchers at Keio University (Japan) coordinated groups to capture the total solar eclipse and then used SAGE to stream high-definition video and still images to Chicago, where SAGE Visualcasting was used to forward the images to Amsterdam. The above photo shows the solar eclipse images on EVL's LambdaVision display; the window in the upper right is an HD video from SARA in Amsterdam, showing them viewing the images as well.

HD video (motion-picture XD-CAM) was captured and transmitted in real time from Wuhan and Shanghai in China, and from Amami, Japan (southern islands), back to Keio University in Tokyo. High-resolution still images were also recorded and transmitted in real time from each location (Nikon D3 with fish-eye lens). From Keio, HD video was streamed using SAGE to a SAGE Bridge cluster at StarLight in Chicago (Keio selected and switched the various input streams). SAGE Visualcasting then replicated the HD video streams for viewing at EVL in Chicago, University of Michigan in Ann Arbor, and SARA in Amsterdam. Uncompressed YUV422 video at ~ 20 fps, with audio, requires a sustained bandwidth of 800Mbps. In addition, digital still images were sent to a SAGE Bridge cluster at EVL using Keio's virtual file-system cache, which uses Fuse, where Visualcasting then replicated the still images to displays at EVL, Michigan and SARA. Images were backed up on EVL's storage system. Uncompressed RGB images at ~1 fps requires a sustained bandwidth of 500Mbps. Keio also arranged to have the event shown on several dome theaters in Japan and to transmit an Internet video stream as well.

July 22, 2009. EVL hosted tours/demos for Illinois' Project Lead The Way (PLTW), a two-week summer institute for high school teachers held at UIC. OptIPuter technologies were featured.

July 21, 2009. The National LambdaRail newsletter published the article "National LambdaRail and Calit2 to Collaborate on End-to-End Research Cyberinfrastructure Platform" featuring OptIPuter efforts <http://www.nlr.net/release.php?id=46>.

July 19-23, 2009. Alan Verlo attended the Summer '09 ESCC/Internet2 Joint Techs in Indianapolis, Indiana.

July 18, 2009. EVL conducted tours and demos as part of *Science Chicago,* showcasing OptIPuter technologies.

June 3, 2009. The UIC Department of Earth and Environmental Sciences brought several visitors from Vietnam to EVL for tours and demos: Nguyen Duy Ngoc, IMC director; Nguyen Hoang, IMC, deputy director; Bui Viet Duc, MSc. Head of IMC Education Exchange Division; and, Dao Dang Toan, IMC, communication assistant. IMC is the Institute for Technology Development, Media and Community Assistance, a division of VUSTA, the Vietnamese Union of Science and Technology, both Vietnamese ministerial level entities. OptIPuter technologies were featured.

May 26, 2009. TheHottestGadgets.com <http://thehottestgadgets.com/2008/06/15-dazzling-multi-monitor-setups-00848> published an online article listing the top 15 dazzling multi-monitor setups found. Two of the 15 were OptIPortals: the MiniMe 30-Megapixel 15-monitor system at the UCSD Scripps Visualization Center <http://siovizcenter.ucsd.edu/minime/> and the UCSD Scripps' Institute of Geophysics and Planetary Physics iCluster 50-Megapixel display <http://siovizcenter.ucsd.edu/icluster/>.

May 21, 2009. EVL hosted demos and tours for people attending the workshop "The Future of New Media," held prior to the annual International Communication Association (ICA) meeting, held in Chicago this year. OptIPuter technologies were featured.

May 1, 2009. Larry Smarr gave the keynote "Digital Cinema and New Media Arts at Calit2" at the Retreat of the Interdisciplinary Film and Digital Media Program, University of New Mexico, Albuquerque, NM.

May 1, 2009. Maxine Brown attended the meeting on Evolutionary Tree Visualization, organized by the Encyclopedia of Life (EoL)/Tree of Life (ToL) tree visualization group and held at the Field Museum in Chicago. She gave a presentation on OptIPuter technologies.

March 25, 2009. Larry Smarr gave the invited talk "Supercomputers and Supernetworks are Transforming Research" at the conference Computing Research that Changed the World: Reflections and Perspectives, held in Washington DC.

March 24, 2009. The National LambdaRail (NLR) All Hands Meeting was held at UCSD/Calit2. Tom DeFanti coordinated OptIPuter-related demos.

March 10-11, 2009. OptIPlanet Collaboratory participant Mikhail Zhizhin, head of the Grid laboratories at the Geophysical Center and the Space Research Institute, Russian Academy of Sciences, visited EVL to discuss OptIPortals, SAGE, applications and future collaborations.

March 1, 2009. Larry Smarr gave the invited presentation "Making Sense of Information Through Planetary Scale Computing" to the Diamond Exchange – Brave New World, Monterey, CA.

February 22-24, 2009. Larry Smarr, Tom DeFanti, Maxine Brown, Jason Leigh, Luc Renambot and others participated in the ON*VECTOR Photonics Workshop, held at UCSD. Jason Leigh gave the presentation "SAGE for CSCW." Tom DeFanti spoke about the "GreenLight Project" and Larry Smarr spoke about "What I've Learned about 'Green'."

February 21, 2009. EVL conducted tours and demos as part of *Science Chicago,* showcasing OptIPuter technologies <http://www.sciencechicago.com/civicrm/event/info?reset=1&id=7686&topic=>.

February 20, 2009. Larry Smarr gave the presentation "The Strongly Coupled LambdaCloud" to the TTI/Vanguard group, La Jolla, CA.

February 9, 2009. Alan Verlo participated remotely in the public event: "Collaborative Expedition Workshop #80, Leveraging SOA: Advancing Cyberinfrastructure Capabilities for High-Performing Distributed Communities," organized by the US General Services Administration.

February 3, 2009. Larry Smarr gave the invited presentation "Restructuring Campus CI – UCSD: A LambdaCampus Research CI and the Quest for Zero Carbon ICT" to the Net@EDU Campus Cyberinfrastructure Working Group, Tempe, AZ.

February 1-5, 2009. Alan Verlo participated in the Winter '09 ESCC/Internet2 Joint Techs, held in College Station, TX. On February 2, he attended the JET meeting.

December 16, 2008. Larry Smarr gave the invited presentation "Shrinking the Planet – How Dedicated Optical Networks are Transforming Computational Science and Collaboration" to the NSF Advisory Committee on Cyberinfrastructure.

December 10, 2008. Tom DeFanti and Maxine Brown participated in an IRNC phone call.

December 9, 2008. Larry Smarr gave the presentation "Shrinking the Planet: A New Global Research Platform – Dedicated 10Gbps Lightpaths" at the TTI/Vanguard "NextGens Technologies" conference in Phoenix, AZ.

December 7-10, 2008. The CineGrid International Workshop 2008 was held at UCSD, La Jolla, CA. Larry Smarr gave the invited presentation "The OptIPlanet Collaboratory – a Global CineGrid Testbed." Jason Leigh of EVL gave the presentation "VizCasting using SAGE with 4K displays – Sharp Labs & UIC/EVL." Luc Renambot of EVL gave the presentation "SAGE 4K DXT Player." Alan Verlo was instrumental in setting up a demonstration among NTT and Keio University (Japan), Calit2 (San Diego) and EVL (Chicago) to demonstrate 4K/2K teleconferencing.

December 4, 2008. EVL hosted a meeting of the Chicago Science Writers organization, and gave tours and demos

that showcased OptIPuter technologies.

November 15-21, 2008. Calit2 and EVL shared a research booth with SDSC during SC08, held in Austin, TX <http://sc08.supercomputing.org>. Calit2 had its OptIPortal running CGLX and EVL worked with corporate partner Sharp Laboratories of America to run SAGE Visualcasting on Sharp's prototype 4K (8-Megapixel) display. Jason Leigh and Luc Renambot entered "Global Visualcasting – Collaborative Remote Visualization Over High Speed Networks" in the SC08 Bandwidth Challenge (BWC), and were one of six Finalists. The BWC, a major annual forum for showcasing leading-edge, international, networked applications, is a friendly yet spirited competition. [Note: The SC08 BWC winner was OptIPuter partner Bob Grossman, who demoed "Toward Global Scale Cloud Computing: Using Sector and Sphere on the Open Cloud Testbed," which connected Calit2, EVL, StarLight and Johns Hopkins University with 10Gbps optical network]

Sachin Deshpande of Sharp Labs and Luc Renambot of EVL holding the SC08 BWC Finalist award in front of the Sharp 4K display running SAGE Visualcasting

Joe Keefe and Trish Stone of Calit2/UCSD ran applications on the Calit2 OptIPortable during SC08

In "Global Visualcasting" demonstrations, EVL streamed 4K and Full HD video, audio and visualizations among three booths on the SC08 show floor in Austin (the SARA, KISTI and EVL/Calit2/SDSC booths), two Midwestern universities (UIC and University of Michigan), and Masaryk University in the Czech Republic and University of Queensland in Australia, to create a sustained global teleconference sharing visualizations of massive datasets.

November 10, 2008. Larry Smarr participated in the panel "A New Global Research Platform – Dedicated 10Gbps Lightpaths" at the Symposium "How Will the U.S. Elections Change US-China Cooperation?" held at Tsinghua University, Beijing, China.

October 29, 2008. Larry Smarr was the featured speaker at EDUCAUSE 2008 and gave the presentation "Preparing Your Campus for Data Intensive Researchers," Orlando, FL.

October 1-2, 2008. Tom DeFanti (Calit2) and Maxine Brown, Jason Leigh, Luc Renambot and Alan Verlo (EVL) attended the 8th Annual Global LambdaGrid Workshop in Seattle, WA, organized by the Global Lambda Integrated Facility (GLIF). Brown is co-chair (with Larry Smarr) of the GLIF Research & Applications Working Group, and organized sessions in which attendees presented their latest efforts to develop applications for LambdaGrids.

2.B. Research Findings

2.B.1. The OptIPortal

2.B.1.1. EVL Cyber-Commons

As a consequence of OptIPuter research, there has been increasing adoption of high-resolution tiled displays in a variety of disciplines, such as geoscience, atmospheric science, astrophysics, and bioscience. We call our tiled displays *OptIPortals* because they are the visual interface devices for the OptIPuter, a global-scale computer tied together by optical networks using the Internet Protocol (IP). There are currently about 60 OptIPortals worldwide.

While OptIPuter funded SAGE software development, the OptIPortal design was based on a 2002 NSF award to EVL for *LambdaVision*[1], a 100-Megapixel tiled display. One of EVL's original goals was that by the end of this award, we would be able to use seamless tiled displays and thin computing clients to build a tiled wall. However, the market did not to make seamless OLEDs available, as previously predicted by market experts. Then, earlier this year, NEC announced new ultra-thin bezel LCD displays with ~0.35mm thick borders.

In Summer 2009, EVL built LambdaVision2, a 20x6-foot tiled display wall that uses NEC displays, whose inter-tile borders are 7mm thick when tiled edge-to-edge within the framing, virtually eliminating the "window pane" effect of LambdaVision's noticeable 35mm tiled borders. The scale and configuration of LambdaVision2 is optimized for a class of 40 students. It was designed so that a single computer can drive all 18 displays (the easy-to-use and economic version), or it can be driven by a cluster connected to high-speed networks so that SAGE can be used to create *cyber-mashups,* or montages of streamed and local high-resolution digital media and information, in addition to accessing websites, PowerPoint slides, and students' laptop display screens.

EVL Professor Johnson uses LambdaVision2 and SAGE to teach the CS course Visualization and Visual Analytics.

EVL's Cyber-Commons room, a high-tech classroom and meeting space, is outfitted with the LambdaVision2 OptIPortal and 20Gbps of networking. *Cyber-Commons* is EVL's term for a technology-enhanced meeting room that supports local and distance collaboration and promotes group-oriented problem solving. At EVL, it provides a community resource openly accessible to faculty and students, where they gather, meet, study, and work.

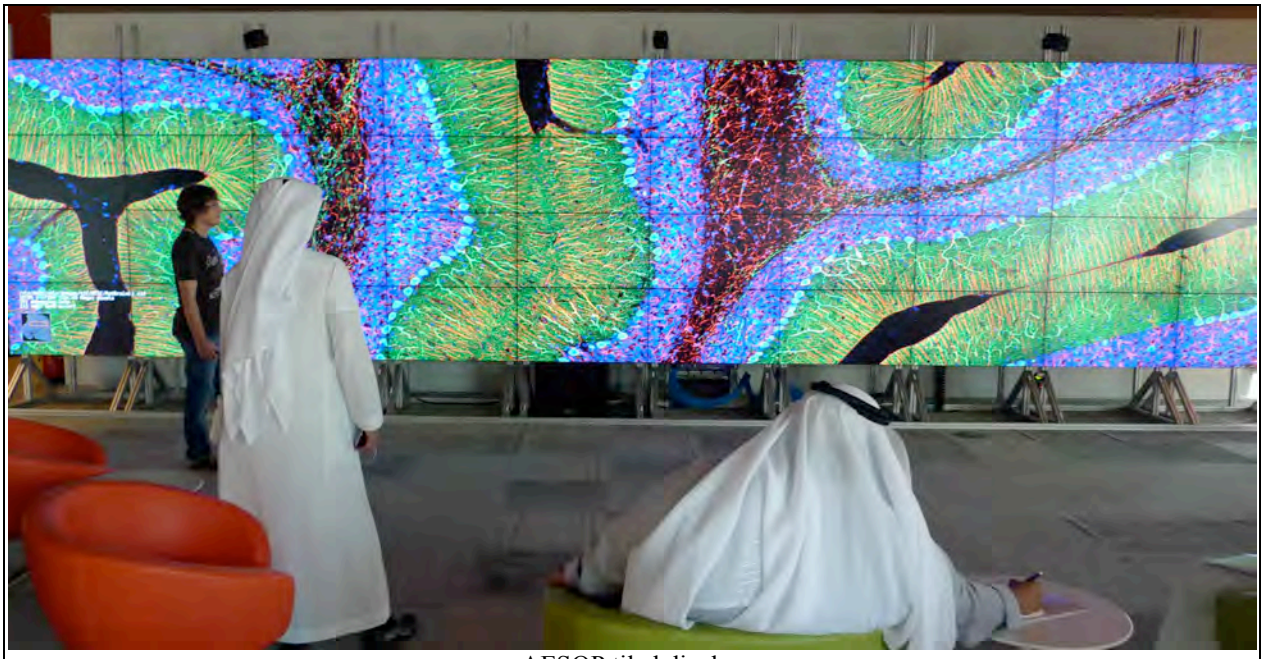
2.B.1.2. Calit2 and KAUST

Saudi Arabia inaugurated the King Abdullah University of Science and Technology (KAUST) on September 23, 2009. The systems for the Visualization Laboratory Showcase were developed and fully prototyped earlier this year at the KAUST-funded VirtuLab at Calit2[2] and at EVL. A 10-person team from Calit2 and EVL spent much of August and September in Saudi Arabia working with the KAUST visualization team as the facilities were constructed, tested and finally displayed to the media and guests during the opening ceremonies.

The visualization facilities developed for KAUST include: CORNEA, a 10-ft. cube of screens forming a 6-sided virtual-reality environment derived from the CAVE invented by EVL; the 21-tile NexCAVE (which stands for "NewXpolCAVE," with Xpol being short for micropolarization) scalable, modular 3D environment; REVE (which stands for "Rapidly Expandable Virtual Environment"), which uses passive 3D technology to present limited autostereoscopic images to the viewer without the use of special glasses; the 40-tile AESOP (which stands for "Almost Entirely Seamless OptiPortal") that features the NEC displays with extremely narrow bezel edges; and, two 3x4-tile OptIPortals (made of 52" NEC displays). The tiled display systems, which represent 2D and 3D stereoscopic) are essentially all OptIPortals, and run CGLX and/or SAGE. Pictures of AESOP and NexCAVE appear below.

[1] Jason Leigh (UIC), PI, received NSF CNS-0420477, September 15, 2004 – August 31, 2009, for LambdaVision.
[2] Tom DeFanti (UCSD), PI, receives KAUST funding for "Calit2 OptIPresence," October 1, 2008 – September 30, 2012. UIC/EVL receives a subaward.

KAUST also acquired a 10Gbps international network circuit from its campus to NetherLight, where it connects to the global GLIF fabric. This circuit became operational in October 2009, and will be used for regular teleconferencing meetings as well as joint research and development activities. For further information, see <www.calit2.net/newsroom/release.php?id=1599>.



AESOP tiled display

NexCAVE passive stereo OptIPortal with tracking, running COVISE software

2.B.2. SAGE

The rapid adoption of OptIPortals has been due to three factors: the need of scientific disciplines to have visualization instruments that are well matched to handle the volume and resolution of the data they are collecting; the increased affordability of what was once considered high-end display, computing and networking technology; and, the development of OptIPuter middleware to drive these displays.

In working with OptIPuter domain science partners, EVL found that as the number of tiles on the display and the image resolution of data to be displayed increased, the desire and need to show multiple visualizations grew. Increased screen resolution affords the juxtaposition (or Cyber-Mashup) of a wide range of high-resolution data simultaneously for cross-examination, providing a means for research teams to externalize their working memory.

SAGE enables multiple visualizations from multiple sources in a variety of resolutions to be juxtaposed. SAGE's Visualcasting capability enables these Cyber-Mashups to be shared among one or more distantly located OptIPortals. SAGE is by no means the first middleware system to drive tiled display walls. Complementary approaches have existed for some time. Well known tiled display middleware systems include WireGL, Chromium, DMX, Equalizer and CGLX. All these approaches render the visualization at the client end. However, SAGE marks a major departure from the traditional model that expects end users to carry the burden of building and maintaining powerful visualization systems, to one where thin clients act as the conduit to shared cyberinfrastructure.

Comparison of Capabilities of Tiled-Display Middleware Systems				
	SAGE	**WireGL/ Chromium**	**DMX**	**Equalizer/ CGLX**
Support for multi-applications simultaneously	Yes	No	Yes	No
Support for wide collection of applications (not only OpenGL)	Yes	No	Yes	No
Requires high-end GPUs at the client-side to be able to visualize large-scale data	No*	Yes	Yes	Yes
Requires modification of applications	Yes/No	No	No	Yes
Supports Distance Collaboration	Yes	No	No	No
Platforms	Linux/Mac/ Windows	Linux/Mac/ Windows	Linux	Linux/Mac, Windows/Linux
Open Source	Yes	Yes	Yes	Yes/No

* SAGE uses cost-effective scalable thin-clients – so it's up to the user how much they want to spend

The chief advantages of SAGE are: it can run multiple applications simultaneously and allows the user to organize them as windows on an OptIPortal; it does not require that the applications be OpenGL-based, and it works for Linux, Mac and Windows-based applications. SAGE does not require that powerful graphics cards be placed at the clients, but rather leverages networked shared cyberinfrastructure to perform the heavy lifting of converting terabyte/petabyte and eventually exabyte-sized data into visualizations. To take maximum advantage of SAGE's parallel streaming capabilities, a visualization programmer embeds a thin layer of software in his application. Also, real-time frame-buffer capture and forwarding are available in SAGE to enable the streaming of applications without modifying them. Using either of these two techniques, it is possible to interface SAGE with WireGL, Chromium, DMX, Equalizer and CGLX, enabling end users to benefit from the best of all worlds. Moreover, SAGE is completely independent of the way the applications' pixels are generated (software or hardware rendering, GPU or many-core systems, Mac/Windows/Linux operating systems…); hence, it is future proof in a rapidly changing technology landscape. Last, SAGE Visualcasting enables these visualizations to be viewed on multiple OptIPortals simultaneously without modifying any of the applications.

Given the growing OptIPlanet Collaboratory SAGE community, EVL submitted the NSF STCI proposal "OptIPlanet Cyber-Mashup" to continue SAGE development and deployment. It was recently announced that EVL was awarded a 3-year $1.9M grant <www.nsf.gov/awardsearch/showAward.do?AwardNumber=0943559>. In writing the proposal, EVL polled the OptIPlanet's SAGE community about what capabilities and enhancements they wanted to see in SAGE, and they identified four high-priority capabilities required of SAGE: (1) a broader set of authoring capabilities; (2) editing and interaction capabilities for remote control of visualization applications; (3) enhanced, scalable visualization streaming; and, (4) a persistent Visualcasting collaboration service.

Authoring Capabilities: SAGE works by streaming pixel information from the source (a supercomputer simulation, a data storage system, a high-definition camera, etc) – similar in principle to how televisions work, but

from sources and at resolutions far greater than what consumer technology can handle. To date, SAGE only works with a few visualization programs on remote systems, so one new capability is to interface it to more programs so data can be streamed from more applications and more sources. A second capability is to interface SAGE with workflow tools, which scientists use to visually "program" the various steps in complex distributed computations; these tools need to be enhanced to specify output be sent to one or more OptIPortals via SAGE. A third capability is to interface SAGE with other visualization middleware systems that juxtapose information on OptIPortals; these other systems either support limited platforms, run locally, or support only one application at a time, so a SAGE interface will enable more data to be shared cross platform.

Editing and Interaction Capabilities: SAGE currently works like one's laptop windowing system; users manually position and size windows on an OptIPortal display. OptIPortals, however, can be quite large, and many windows can be viewed simultaneously, making it tedious to constantly update; users requested automated assistance to help them organize information. One capability is to develop SAGE-based applications and templates that automatically scale information based on an OptIPortal's size and resolution. In addition, when viewing applications on SAGE-driven displays that have well designed user interfaces, users want to interact with the interface and affect the outcome of the applications. So, a second capability is to enable user interactions within existing applications and to provide APIs to build user interfaces that take advantage of SAGE.

Streaming Capabilities: As content and image resolution increase – so that multiple high-resolution images and/or animations are simultaneously streamed from local and/or remote sources to one or more tiles on an OptIPortal – there is a need for better network protocols to move the information with minimal latency and jitter, and there is a need to more smoothly synchronize the update rate across tiles on a given OptIPortal display wall. The former requires new reliable UDP network protocols be built into SAGE; the latter requires better synchronization techniques to ensure the visual integrity of images across tiles. A third new capability is to include new real-time compression techniques in SAGE, such as JPEG2000, that do not degrade image quality while reducing bandwidth requirements for streaming ultra-high-resolution images/animations.

Collaboration Capabilities: SAGE Visualcasting is a real-time image broadcasting service that enables multi-point collaborative work sessions on variable-sized OptIPortals, without the need for multicast. Users can share high-definition video-teleconferences as well as data to more easily collaborate over distance. SAGE Visualcasting's video and audio communications capabilities need to be hardened, and true multi-channel audio capabilities with advancing mixing (e.g., volume control) and true spatial 3D audio (where an application's audio appears to originate from the physical location of its window on the display) need to be developed.

While the "OptIPlanet Cyber-Mashup" award focuses on EVL's improving and deploying user-requested SAGE capabilities over the next few years, it also focuses on building and expanding the SAGE user community. To do this, EVL will create a wiki to distribute both stable and beta SAGE releases, along with online documentation and tutorials. EVL will track usage by providing an enhanced SAGE Forum and online SAGE Help Desk, and will solicit developer and end-user feedback, both quantitatively, via user surveys, and qualitatively, via experiences and requirements.

EVL will use one of several annual high-performance conferences or workshops (such as the Supercomputing conference, the TeraGrid conference or the Great Lakes Consortium for Petascale Computing [GLCPC] Virtual School's summer workshops), to meet with SAGE users and developers, conduct Birds-of-a-Feather sessions and/or tutorials, and provide overviews of major release features, roadmap updates, and community-built applications. EVL will also investigate holding SAGE Visualcasting campaigns at these conferences, to enable remote users to virtually attend and participate in collaborative sessions.

2.C. Research Training

The initial OptIPuter project has enabled a critical mass of professors and students at eight funded institutions (UCSD, UCI, SDSU, USC/ISI, TAMU, UIC, NU, UIUC/NCSA) and 10 affiliate (unfunded) institutions (NASA, Purdue University, University of Michigan, US Geological Survey, CANARIE [Canada], Communications Research Centre [Canada], SARA Computing and Networking Services [The Netherlands], University of Amsterdam [The Netherlands], KISTI [Korea] and AIST [Japan]) to be involved with OptIPuter research and development, facilitating greater advances than a single-investigator effort would afford. Moreover, the project has been local, regional, national and international in scope. As noted in Section 2.B (Research Findings), all the people working on OptIPuter-related projects are involved in furthering the research, taking a "systems-wide" view of the project, which is clearly interdisciplinary in nature. It is our hope that our students benefit most, and are in high demand by the academic and commercial research sectors for R&D jobs when they graduate.

The OptIPuter has gained international recognition as a major driving force for the development of LambdaGrids. Interest comes from not only computer scientists and network engineers, but also from discipline scientists who are facing unprecedented challenges dealing with large datasets in the 21st century. The OptIPuter involves academicians, graduate students, undergraduates, K-12 teachers and students, and industry. Research papers have been published and presentations have been given at numerous professional conferences.

2.D. Education/Outreach

The OptIPuter's primary education and outreach activities include web documentation, journal articles, and conference presentations and demonstrations. In addition to participation at major computer conferences, such as IEEE ACM/IEEE Supercomputing (SC), team members are active in other regional (CENIC), national and international conferences and workshops (e.g., annual GLIF LambdaGrid Workshops, International Workshop on Protocols for Fast Long-Distance Networks [PFLDnet], High Performance Distributed Computing [HPDC], etc.). The OptIPuter receives a great deal of media attention, and there have been a number of news articles describing it, which can be found on our website <http://www.optiputer.net/news/index.html>. We also provide PowerPoint slides and other promotional material to collaborators to give presentations at education conferences, government briefings, etc.

3. OptIPuter Publications and Products

3.A. Journals/Papers

Pieper, G., T.A. DeFanti, Q. Liu, M. Katz, P. Papadopoulos, J. Keefe, G. Hidley, G. Dawe, I. Kaufman, B. Glogowski, K. Doerr, J.P. Schulze, F. Kuester, P. Otto, R. Rao, L. Smarr, J. Leigh, L. Renambot, A. Verlo, L. Long, M. Brown, D. Sandin, V. Vishwanath, R. Kooima, J. Girado, B. Jeong, "Visualizing Science: The OptIPuter Project," SciDAC Review, Issue 12, Spring 2009, IOP Publishing in association with Argonne National Laboratory, for the US Department of Energy, Office of Science, pp. 32-41, <www.scidacreview.org/0902/index.html>

Smarr, Larry, "The OptIPuter and Its Applications," 2009 IEEE LEOS Summer Topicals Meeting on Future Global Networks, July 22, 2009, pp. 151-152, doi: 10.1109/LEOSST.2009.5226201

3.B. Books/Publications

Alimohideen, J., L. Renambot, J. Leigh, A. Johnson, R. Grossman, M. Sabala, M., "PAVIS - Pervasive Adaptive Visualization and Interaction Service," CHI 06 Workshop on Information Visualization and Interaction Techniques for Collaboration Across Multiple Displays, Montreal, Canada, April 2006

Jeong, Byungil, Visualcasting: Scalable Real-time Image Distribution in Ultra-High Resolution Display Environments, PhD Dissertation, Computer Science, University of Illinois at Chicago, 2009 <http://www.evl.uic.edu/files/pdf/Jeong-SAGE-dissertation-March2009.pdf>

Krumbholz, C., J. Leigh, A. Johnson, L. Renambot, R. Kooima, "LambdaTable: High Resolution Tiled Display Table for Interacting with Large Visualizations," Workshop for Advanced Collaborative Environments (WACE) 2005, Redmond, Washington, September 2005

Leigh, J. A. Johnson, L. Renambot, "Advances in Computer Displays" (chapter), Advances in Computers, Vol. 77, Elsevier/Morgan Kaufman, July 13, 2009.

Leigh, J., L. Renambot, A. Johnson, R. Jagodic, H. Hur, E. Hofer, D. Lee, "Scalable Adaptive Graphics middleware for visualization streaming and collaboration in ultra resolution display environments," Proceedings of the Workshop on Ultrascale Visualization, 2008, UltraVis 2008, Austin, TX, November 2008

Renambot, L., Jeong, B., Jagodic, R., Johnson, A., Leigh, J., Aguilera, J., "Collaborative Visualization using High-Resolution Tiled Displays," CHI 06 Workshop on Information Visualization and Interaction Techniques for Collaboration Across Multiple Displays, 2006

Vishwanath, Venkat, LambdaRAM: A high-performance, multi-dimensional, distributed cache for data-intensive applications over high-speed networks, PhD Dissertation, Computer Science, University of Illinois at Chicago, 2009 <http://www.evl.uic.edu/files/pdf/Vishwanath_PhD_Dissertation_2009.pdf>

3.C. Internet Dissemination

www.optiputer.net

3.D. Other Specific Products

None at this time.

4. OptIPuter Contributions

4.A. Contributions within Discipline

The OptIPuter team's mission has been to enable scientists to explore very large remote data objects in a novel interactive and collaborative fashion, which is impossible on today's shared Internet. This involves the design, development and implementation of the OptIPuter -- a tightly-integrated cluster of computational, storage and visualization resources -- linked over LambdaGrids, parallel dedicated optical networks across campus, metro, national, and international scales. The OptIPuter project has aimed to re-optimize the entire Grid stack of software abstractions, learning how to "waste" bandwidth and storage in order to conserve "scarce" computing in this new world of inverted values. A major outcome of this research was the development of advanced middleware and network management tools and techniques to optimize transmissions so distance-dependent delays are the only major variable. The group of computer scientists and network engineers assembled represent many of this nation's high-performance computing and communications leaders. New collaborators continue to seek out this group's expertise in order to jointly develop a common framework for optimizing optically linked clusters over LambdaGrids.

4.B. Contributions to Other Disciplines

The OptIPuter's mission has been to enable collaborating scientists to interactively explore massive amounts of previously uncorrelated data by developing a radical new architecture for a number of this decade's e-science shared cyberinfrastructure facilities. The OptIPuter's broad multidisciplinary team conducted large-scale, application-driven system experiments with two data-intensive e-science efforts to ensure a useful and usable OptIPuter design: EarthScope, funded by the National Science Foundation (NSF), and the Biomedical Informatics Research Network (BIRN) funded by the National Institutes of Health (NIH). These application drivers have many multi-gigabyte-sized individual data objects -- gigazone seismic images of the East Pacific Rise Magma chamber and 100 megapixel montages of rat cerebellum microscopy images -- which are very large volumetric data objects with visualizations so big they exceed the capacity of the current shared Internet and laptop displays. Over the past few years, new user communities (including the CoreWall/ANDRILL Antarctic geological Drilling Program, CineGrid, CAMERA metagenomics, NASA weather modeling and forecasting, PRAGMA Pacific Rim Application and Grid Middleware Assembly, ROADNet real-time observatories, and Ocean Observatory Cyberinfrastructure) are taking advantage of the architectures developed for the OptIPuter, and creating the nascent OptIPlanet Collaboratory.

4.C. Contributions to Education and Human Resources

The OptIPuter, over its first five years, annually supported, on average, 25 senior faculty and part-time staff and 14 graduate students, spanning 8 institutions. Non-funded faculty, staff and students from 10 affiliate institutions and several industrial partners also worked tirelessly on OptIPuter research. Our efforts in the K-12 public schools (in San Diego and in Chicago) engaged teachers and school children. We have built a worldwide community eager for new methodologies for the real-time exploration of e-science.

No-cost extension funds were applied in Year 6 to staff and graduate students to focus on development and documentation, and assist with deployment efforts. A no-cost extension in Year 7 enabled the team to continue to deploy and harden hardware and software technologies and better understand user requirements.

4.D. Contributions to Resources for Science and Technology

The OptIPuter exploits a new world in which the central architectural element is optical networking, not computers -- creating "supernetworks." This paradigm shift requires large-scale applications-driven, system experiments and a broad multidisciplinary team to understand and develop innovative solutions for a "LambdaGrid" world. The goal of this new architecture is to enable scientists who are generating terabytes and petabytes of data to interactively visualize, analyze, and correlate their data from multiple storage sites connected to optical networks.

While extremely important, bandwidth alone is not the solution. The OptIPuter has worked on new Grid computing paradigms -- new middleware, transport protocols, optical signaling, and control and management software to enable applications to dynamically manage lambda resources just as they do any grid resource, creating a LambdaGrid of interconnected high-performance computers, data storage devices and instrumentation. The OptIPuter project is not

optimizing toward scaling to millions of sites, a requirement for commercial profit, but empowering networking at a much higher level of data volume, accuracy and timeliness for several key high-priority research and education sites.

4.E. Contributions Beyond Science and Engineering

Researchers hope that the OptIPuter, when linked with remote "data generators," whether the TeraGrid, instrumentation or data storage devices, will prove to be an enabling technology for large-scale networked science facilities, as well as for broader societal needs, including emergency response, homeland security, health services and science education.