Larry Smarr

The Emergence of a Planetary-Scale Collaboratory for Data-Intensive Research

Introduction

I had the good fortune to work with Alan Kay as part of the CSC Vanguard team in the 1990s and always valued the insightful critiques he would make of presentations during the Vanguard sessions. Although I knew about Alan's fundamental contributions to user interface design, I came to understand also that he had a longtime interest in developing collaborative multiuser software to support many application areas of interest. This research with his colleagues eventually evolved into the Croquet software development kit (SDK), which can be used to support "highly scalable collaborative data visualization, virtual learning and problem solving environments, three-dimensional wikis, online gaming environments (MMORPGs), and privately maintained/interconnected multiuser virtual environments."[1]

During the two decades that Alan and his colleagues were working on what became Croquet, the two institutes I founded, the National Center for Supercomputing Applications (NCSA) and the California Institute for Telecommunications and Information Technology (Calit2), were also deeply engaged in developing a series of collaboration environments, with a focus

[1] http://en.wikipedia.org/wiki/Croquet_Project

on collaborative analysis of data. Alan's emphasis on simplicity and natural human-computer interfaces made a deep impression on me. I have kept these ideas in mind as the global team I was part of developed a working version of a collaboration metacomputer [16] as big as planet Earth, but with many of same characteristics as a personal computer.

I briefly describe the two tracks we followed: the first was similar to Alan's notion of a collaborative environment for sharing personal computer desktops and the second a series of experiments on *tele-immersion*, innovative software/hardware environments that enable sharing of entire rooms for data intensive analysis using advanced technologies.

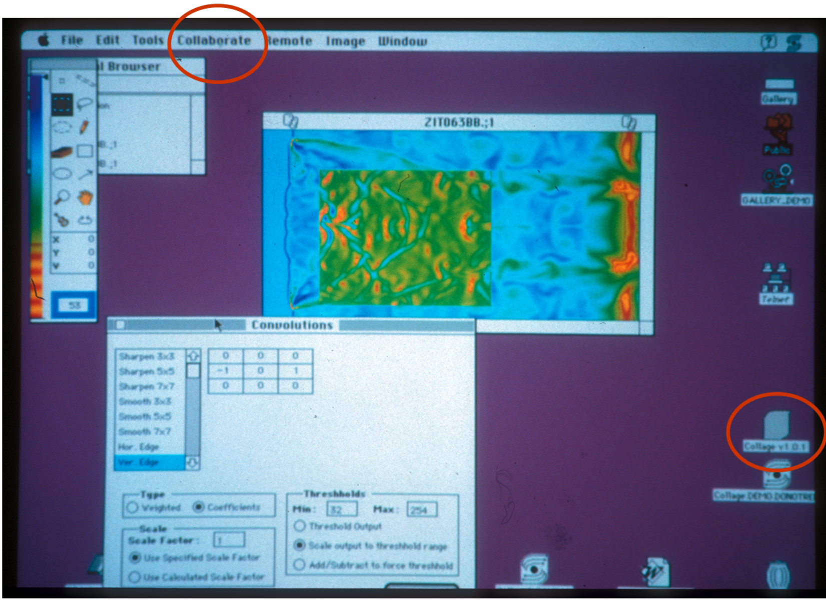
Desktop Collaboration Software Systems

The early 1980s, the period which led to the funding of the National Science Foundation (NSF) supercomputer centers, including NCSA in 1985, coincided with the period of the birth of the IBM PC and the Apple Macintosh. I had early versions of both, even as I was advocating for a national supercomputer with a cost over $10 million. Even though the computational scientists needed access to powerful vector computers, I was convinced that the correct user interface was through the personal computer. So our NCSA software development team started using the phrase "Hide the Cray," by which we meant making the remote supercomputer appear as an icon on the network-connected PC or Mac. This concept led to the development by NCSA staff of NCSA Telnet,[2] which allowed multiple remote sessions to be run from a PC or Mac.

In the late 1980s a whole series of PC and Mac software was turned out by NCSA, such as NCSA Image, bringing the flexibility of the Mac to visual and analytic analysis of complex data, often generated by our supercomputers. By 1990 the NCSA Software Development Group (SDG), led by Joseph Hardin, had created NCSA Collage, which was synchronous desktop collaboration

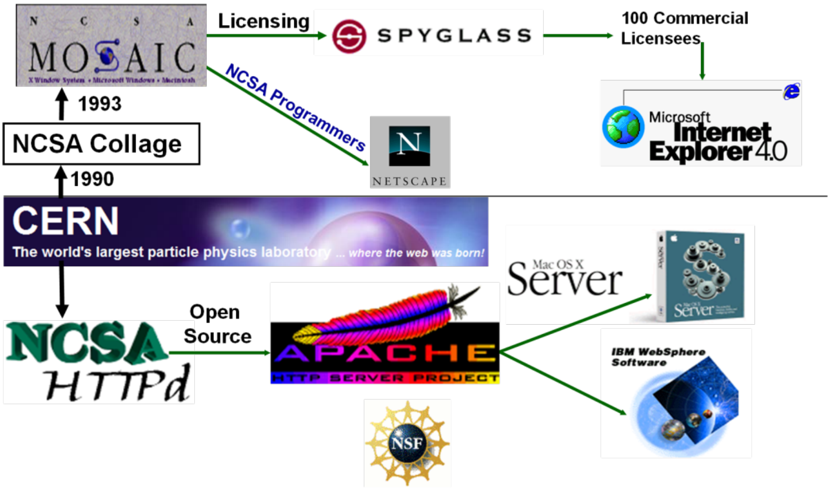
[2] http://en.wikipedia.org/wiki/NCSA_Telnet

software which could run on Windows, Mac OS, and UNIX. Collage built on the graphic interface ideas in the previous software tools, but provided a common windowed view to collaborating users with shared white boards, image display and analysis, color table editing, and spreadsheet display of floating-point numbers. The image below (from Susan Hardin, NCSA) shows a screen capture of NCSA Collage for the Mac. I have circled the "Collaborate" tab on the menu line and Collage's icon which appears as just another desktop application.



With the development by CERN's Tim Berners-Lee of the Web protocols in 1990, the NCSA SDG realized they could introduce not only documents into Collage, but hyper-documents as well, and set up a sub-project to develop the needed software. This project, NCSA Mosaic, quickly became a world of its own as two members of the Mosaic team, Marc Andreessen and Eric Bina, developed the Unix Mosaic browser and began releasing it in 1993. Their NCSA Mosaic group grew and soon the HTTPd Mosaic server software, as well as Windows and Mac versions of the Mosaic browser, were made available.

The ability to download freely both a graphical web browser and server software set off exponential growth in the number of people making their own web sites and viewing others. NCSA's web server became the most visited web site in the world, leading us to develop the world's first parallel web server. The rest is history (see diagram below). Andreessen and Bina joined Jim Clark in founding what became Netscape, Microsoft licensed Mosaic through Spyglass, a local company that had taken over licensing from the University of Illinois, and the Apache Software Foundation created the Apache server from the open source Mosaic server software.



Yet in spite of the global transformational nature of Mosaic and its progeny, NCSA Collage attracted very few synchronous collaboration users. It was time consuming for the NCSA SDG to keep the three separate code bases developed in parallel and so eventually the development on Collage ceased. Somehow, the lesson was that single-user personal computer software is adopted much more readily than collaboration software.

With the announcement of Java by Sun Microsystems in the early 1990s, the NCSA SDG realized it could have just one software base for building collaboration software, which would be automatically cross-platform. The introduction of Java led to the NCSA Habanero project [17] in 1995, which recreated the NCSA Collage functionality, but written entirely as a Java application. The Habanero software system provided the necessary framework in which one could create collaborative work environments and virtual communities, as well as to transition existing applications and applets into collaborative applications. At the time, Habanero was perhaps the largest single Java application yet written. However, in spite of the Wall Street Journal in 1996 saying, "NCSA hopes Habanero will take the Web one step further—into collaboration," its use was quite limited and again development eventually stopped.

Although it was frustrating to me that in spite of how useful these collaborative software systems were, they did not take off in adoption like the web browser, it was still clear to me when I watched people using synchronous collaboration software that sooner or later this is what software and the Internet were destined to make possible. Since full desktop collaboration systems are still not widely used, nearly twenty years after NCSA Collage appeared, perhaps we were just a bit too early in our view of what the Internet could make possible...

Perhaps more successful in terms of adoption was a parallel track at NCSA, starting a little before the NCSA Collage project, which was to build collaboration environments using the most advanced technology available that would "sew" whole rooms together, whether those rooms were physical or virtual, to allow for tele-immersive collaborative analysis of data-intensive research.

A Vision of the Collaborative Future

The first prototype of this idea was produced in 1989 when NCSA, together with Sun Microsystems and AT&T, put on a demonstration termed *Televisualization: Science by Satellite*, which was meant to illustrate how collaborative use of high performance computing with visualization might be made possible in the future using fiber optic networks. Since availability of those networks for academic researchers was a decade in the future, we conceived of using analog video technology, transmitted over TV satellites, to emulate that future. AT&T put large satellite dishes next to NCSA in Champaign, Illinois and outside Boston's Museum of Science, close to the SIGGRAPH'89 meeting, to establish the link from UIUC to Boston.

UIUC Professor of Theoretical and Applied Mechanics Bob Haber used a track ball on stage to send commands over a 9,600 baud return dial-up line to rotate a dynamic visualization being computed on an Alliant FX graphics mini-supercomputer, which was creating a visualization of the simulation of a crack propagation in a plate being computed in real-time on a Cray-2 supercomputer at NCSA. All the while (see screen capture image), there was a larger-than-life video image of Professor Bob Wilhelmson at NCSA on the stage (center) in Boston discussing the event with Donna Cox (extreme right), Bob Haber (standing left), and myself (center right). While we had to use an analog video stream sent by satellite to emulate the future digital transmission of data, reviewing the recording of the event[3] is eerily similar to what we actually can do today with 10 Gbps dedicated fiber optic networks, as described later.

As then-Senator Gore said in a pre-recorded video played as part of the demo, "[we were] using satellite technology ... to create a demo of what it might be like to have high-speed fiber-optic links between advanced computers in two different geographic locations." I stated during the demo, "What we really

[3]Video of the session is available from Maxine Brown, EVL, UIC. A digitized version can be viewed at: `http://www.youtube.com/watch?v=3eqhFD3S-q4`

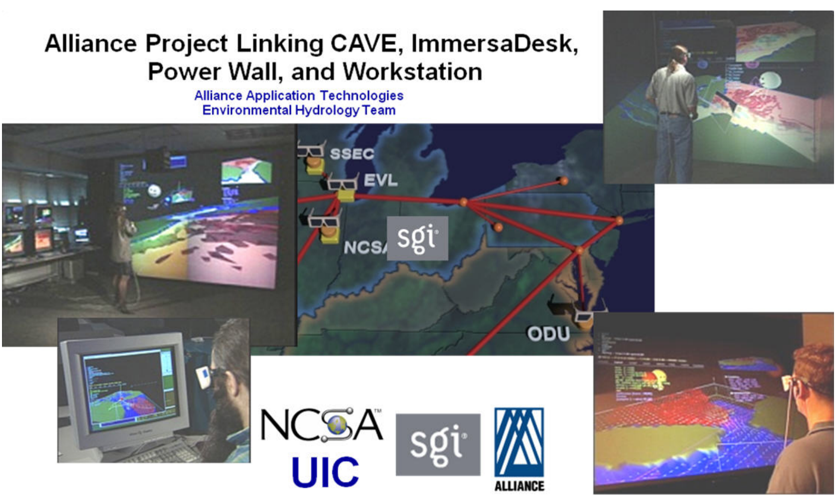
have to do is eliminate distance between individuals who want to interact with other people and with other computers." This has been the holy grail of the next two decades of research that I have pursued with my co-workers.

Leading-Edge Collaboration Environments: Shared Internet

The development of Silicon Graphics computers, putting the power of a graphics mini-supercomputer into a workstation, enabled new immersive versions of virtual reality (VR) to be conceived, such as the CAVE [18] and ImmersaDesk [19] created by Tom DeFanti, Dan Sandin, and their colleagues at the University of Illinois at Chicago's Electronic Visualization Laboratory (UIC/EVL) in the early 1990s. These various interactive stereo interfaces used the CAVELibrary [20] VR software API to display images on the walls of the CAVE, and the CAVERNsoft library [21] to link remote virtual spaces over networks. In 1996, NCSA industrial partner Caterpillar [22] used ATM networks between Germany and NCSA to support a collaborative VR session containing a three-dimensional stereo life-size rendering from a CAD database of a new earth mover. In this shared data-space, Caterpillar used video streams as avatars to represent the remote participant, creating arbitrarily oriented virtual video screens floating in the shared virtual space. With this international collaborative VR infrastructure they discussed possible CAD modifications so as to make maintenance easier in the field. Caterpillar was an innovative industrial partner, driving virtual reality advances at NCSA for over a decade.

By 1997, the NSF had expanded two of the NSF supercomputer centers, NCSA and SDSC, into Partnerships for Advanced Computational Infrastructure (PACI). The PACIs were able to use the newly NSF-funded very high-speed Backbone Network Service (vBNS)[4] to explore innovative modes of collaboration. The NCSA PACI was called the Alliance and one of its first activities was developing tele-immersion [23]—the union of audio and video conferencing, networked collaborative VR, and image-based modeling for data-intensive applications.

Tele-immersion was accomplished by combining CAVERNsoft with specific application domain visual analysis software, such as the Vis5d,[5] an OpenGL-based volumetric visualization program for scientific datasets in three or more dimensions, to form CAVE5D.[6] CAVE5D was augmented with remote interaction techniques and camera choreography capabilities provided by the VR application Virtual Director developed by Donna Cox, Bob Patterson, and their co-workers at NCSA, with colleagues and students at UIC/EVL.[7] All this was run over the vBNS, which supported speeds of 155 to 622 Mbps on the shared Internet.



[4]`http://www.nsf.gov/od/lpa/nsf50/nsfoutreach/htm/n50_z2/pages_z3/47_pg.htm`

[5]`http://vis5d.sourceforge.net`

[6]`http://www.mcs.anl.gov/đmickelso/CAVE2.0.html`

[7]Virtual Director was originally created at NCSA by Donna Cox, Bob Patterson and Marcus Thiebaux. The software was further developed by Cox, Patterson, Stuart Levy and Matthew Hall.

In the image above one sees Donna Cox in front of a PowerWall (tiled wall with rear video projectors upper left), Bob Patterson in a CAVE (upper right), Stuart Levy at a workstation (lower left), and Glen Wheless at an ImmersaDesk (lower right). Donna, Bob, and Stuart are all at different locations at NCSA and Glen is at Old Dominion University in Virginia. They are sharing the Virtual Chesapeake Bay,[8] a visual representation of data produced by a coupled physical/biological simulation, using Virtual Director to navigate the space; it could also record the session. Note the three-dimensional smiley face avatars floating in the various spaces, which represent the location in the 3-space of the remote collaborators.

Argonne National Laboratory (ANL) drove the next stage of innovation for tele-immersion, utilizing the vBNS capability to use IP Multicast to develop the Alliance Access Grid (AG), which allowed a large number of sites to join into a collaborative session, each with its own video and audio streams. Development of AG was led by ANL's Rick Stevens and its Math & Computer Science Division, one of the principle Alliance partners, as a part of the Alliance National Technology Grid. It has been widely used over the last decade to support multi-site video conferencing sessions. The image above was taken during one of the Alliance digital "chautauquas"[9] on September 14, 1999. The

[8] http://www.computer.org/portal/web/csdl/doi/10.1109/38.511854

[9] http://access.ncsa.illinois.edu/Releases/99Releases/990713.Grid.Chautauqua.html

collage of live video feeds shows me giving a lecture from Boston University (along with my streaming Power Point slides) and multiple video feeds from six sites across the U.S. (including Rick at ANL left and below me), plus one from Moscow in Russia (left of me).

Thus, besides driving the early use of IP multicast video streams over the Internet, the Access Grid also drove early international video collaborations using the Internet. To provide a national and international peering point for advanced research and education networks, NSF funded the Science, Technology, And Research Transit Access Point, or STAR TAP,[10] located in Chicago and managed by the UIC's EVL and ANL, with Ameritech Advanced Data Services. STAR TAP grew into a major exchange for the interconnectivity and interoperability of both national and international research networks. The Alliance Access Grid used the STAR TAP to support the broad collaboration shown in the image.

High Performance Collaboration Environments: Dedicated Internet

At about the same time that the AG took off, our team realized that the traditional shared Internet was blocking innovation. We wanted to keep the Internet Protocol, but the enormous build-out of fiber optics in the 1990s meant we no longer needed to live in a "bandwidth scarcity" regime. Rather, by doing the heretofore unthinkable, giving a fiber, or at least a 10 Gbps wavelength on the fiber, to an individual user, we could jump several orders of magnitude in bandwidth capability into the future. In Illinois NCSA, ANL, and EVL worked with the Governor's office to create the IWIRE[11] "dark fiber" network for the state. About the same time Indiana created the I-Light fiber network. Today there are over two dozen state and regional optical research and education networks.

This major change in architecture of the Internet, arguably the biggest change since the creation of the Internet, created global availability of dedicated

[10] http://www.startap.net/startap

[11] http://www.iwire.org

1 Gbps and 10 Gbps optical fiber networks, providing a research network parallel to the shared Internet, but used only by researchers engaged in data-intensive projects. These networks retain the Internet Protocol in the Internet Layer of the Internet Protocol Suite, but do not necessarily use TCP in the transport protocol layer. Whereas the traditional shared Internet traffic uses Layer 3 in the OSI Model, the dedicated optical networks most often use Layer 2 or even Layer 1.

The usual mode of usage is to have a point-to-point uncongested optical link, or a few such fixed links, which means that there is fixed latency, removing jitter. Finally, the bandwidth available to a single user is between a hundred and a thousand times that of the jittery shared Internet, which typically provides end-users only tens of Mbps bandwidth. This gets around a lot of the technical difficulties experienced by the AG, since streaming media is now predictable, high speed, and jitter-free. Also it changes the mode of moving gigabyte- to terabyte-sized data objects from FedEx to FTP. For instance, it takes ten days to move a 1 TB data object over 10 Mbps (typical of today's shared Internet), whereas it takes approximately 10 minutes over a 10 Gbps lambda.

In the early 2000s there was a rapid growth of state and regional networks (e.g., CENIC in California, Pacific Wave in the Northwest), national networks (National LambdaRail, NLR, and more recently the Internet2 Dynamic Circuit Network, I2DCN), and international interconnection networks (Global Lambda Integrated Facility, GLIF) which led to an explosion of innovation and experimentation. For instance, by iGrid 2005,[12] hosted by EVL's Maxine Brown, Tom DeFanti, and myself, in the new UCSD Calit2 building, there were fifty real-time application demonstrations from twenty countries [24]. This included the first transpacific transmission of the new 4K digital cinema (approximately 4000 by 2000 pixels at 24 frames per second), compressed using NTT Network Innovation Laboratories' JPEG2000 codecs to streams of about 0.5 Gbps running over dedicated gigabit fiber channels between Keio University in Japan and Calit2 at UCSD.

[12] http://www.igrid2005.org

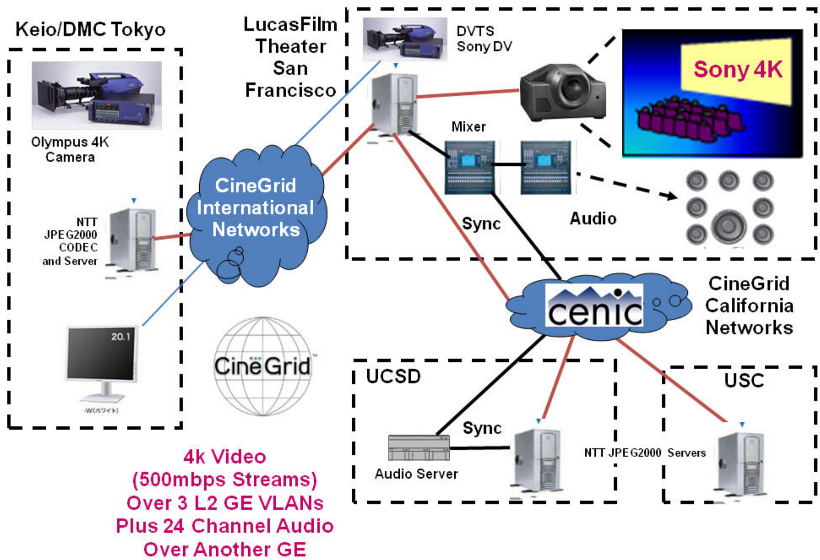
This new-found ability, to have jitter-free optical paths that have larger bandwidth than the underlying high-resolution video and audio streams, meant that digital media artists became one of the major drivers of this new collaborative fabric. In particular, universities and private sector companies from the U.S., Canada, Japan, and the Netherlands came together to form a non-profit project called CineGrid [25].[13] CineGrid's mission is "to build an interdisciplinary community focused on the research, development and demonstration of networked collaborative tools, enabling the production, use and exchange of very high-quality digital media over high-speed photonic networks." It has an annual meeting every December hosted by Calit2 at UCSD. This brought the focus of a wide community of practice on new forms of digital collaboration.

As an example, one year after iGrid 2005, on October 25, 2006, the CineGrid team set up four dedicated gigabit Ethernet vLANs to form a collaborative network between Keio University's Research Institute for Digital Media and Content (Tokyo), Lucasfilm's Letterman Digital Arts Center (LDAC in San Francisco), USC's School of Cinematic Arts (Los Angeles), and Calit2 (San Diego).[14] Working with engineers from ILM and Skywalker Sound, the CineGrid team re-configured the LDAC Premier Theater, normally used to show traditional movies, to enable network delivery of up to 10 Gbps for real-time playback and control of 4K digital motion pictures and 24 channels of uncompressed, 24-bit digital audio from three remote sites. Then for the first time, 2K (HD) and 4K (digital cinema) resolution digital motion pictures and 24-channel digital audio were streamed from three different locations in real time, then synchronized and mixed live for an Audio Engineering Society audience in the LDAC Theatre.

Chris Sarabosio, a sound designer at Skywalker Sound, said: "With the experimental system used at the CineGrid@AES event, I was able to control playback and mix 24-channel audio interactively while watching the synchronized picture on the big screen just like I do normally, only this time the audio

[13] http://www.cinegrid.org

[14] http://www.calit2.net/newsroom/article.php?id=958



servers were 500 miles away connected by CineGrid. This approach clearly has the potential to eliminate distance as a barrier to collaboration."

The beginning of the rise of the new optical fiber Internet infrastructure led me in 2001 to organize what became the NSF-funded OptIPuter project[15] [26], which supported major teams at Calit2 and EVL plus a number of other academic and industrial partners. The application-driven OptIPuter project set out to explore how the availability of these new dedicated 10 Gbps Internet lightpaths ("lambdas") [27] would transform data-intensive science. Use of these lambdas provided end-users "clear channel" access to global data repositories, scientific instruments, and computational resources from the researchers' Linux clusters in their campus laboratories. These clusters can be configured as "OptIPortals" [28], providing the end users with local scalable visualization, computing, and storage. Using the 10 Gbps lightpaths available over the NLR, I2DCN, and GLIF, this new distributed architecture creates an end-to-end "OptIPlatform" for data-intensive research [29].

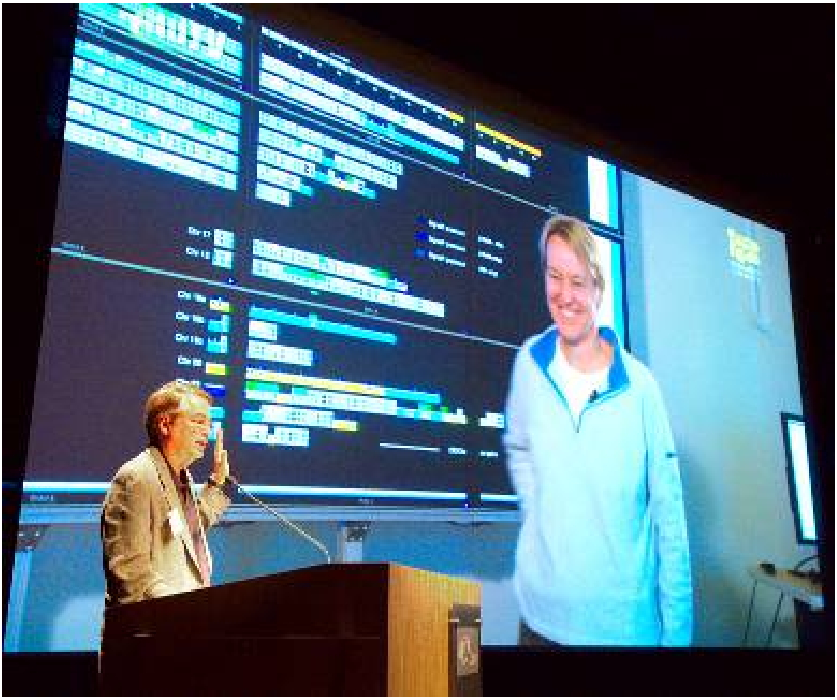
[15] http://www.optiputer.net

For collaboration purposes, the OptIPlatform is being used today for combining high-resolution video streams (HD, 4K) with OptIPortals in a variety of ways, so that virtual/physical workspaces can be established on demand. We have been fortunate to work with the talented group at the University of Michigan, which has multiple OptIPortals, and a long and distinguished history of research on scientific collaboration modes, to better define the social science and human interface issues. The psychological effect for end-users is that their rooms are "sewn together," regardless of distance, and massive amounts of data can be interactively visualized and shared—essentially realizing the vision of the Science-by-Satellite experiment twenty years ago. The manner in which the audio-video streams are coupled with the OptIPortals or CAVEs is an area of active research, so I will end by briefly describing three current modalities.

First, rooms such as auditoriums that have HD or 4K projectors can use optical networks to link to remote sites that have OptIPortals. The video streams can range from heavily compressed commercial H.323 (typically less than 1 Mbps) up to uncompressed (1.5 Gbps HD) video. In the photo we see Professor Ginger Armbrust at the University of Washington explaining to me in the San Diego Calit2 auditorium the single nucleotide polymorphisms which are marked along the chromosomes of the diatoms she is visualizing on her OptIPortal. Using the methodology developed by the UW Research Channel, we are using an uncompressed HD video stream to link her lab with the Calit2 auditorium using a point-to-point 10 Gbps lambda over CENIC and Pacific Wave optical fiber infrastructure [30]. This experiment was in support of the Moore Foundation-funded Community Cyberinfrastructure for Advanced Marine Microbial Ecology Research and Analysis (CAMERA) project. This method has also been used extensively, with different levels of HD compression, between the two Calit2 campuses, Calit2 and Australia, and Calit2 and NASA Ames [31].

The Scalable Adaptive Graphics Environment[16] (SAGE) developed for the OptIPortal by EVL enables the highest performance version of lambda

[16] `http://www.evl.uic.edu/cavern/sage`

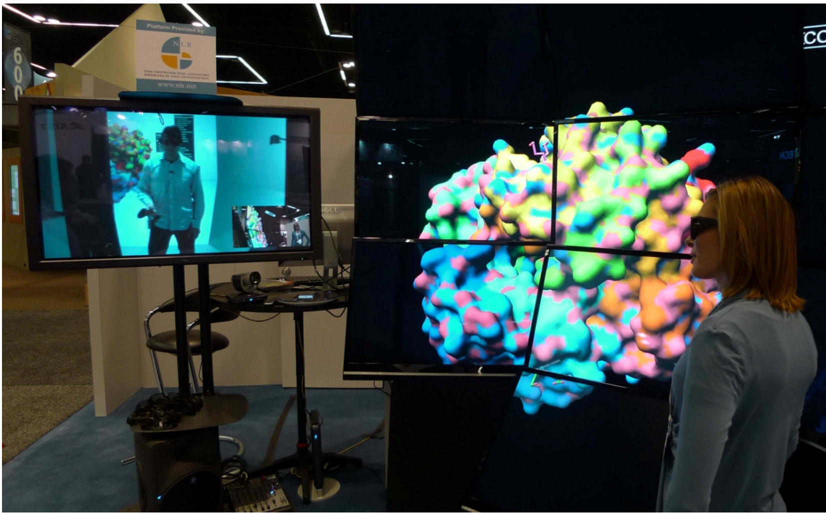


collaboration yet through its Visualcasting [32] feature, which distributes HD video and visualizations in real time to multiple sites. It does not require IP multicast in routers as Access Grid did, but rather achieves multicast by using commodity clusters (SAGE Bridges) to replicate and to broadcast real-time ultra-high-resolution content to multiple sites. To scale up the resolution or number of sites, one just increases the number of cluster nodes.

The photo below was taken during an HD teleconference at EVL in Chicago. One sees on the EVL OptIPortal behind EVL director Jason Leigh the HD video streams from lambda connections to University of Michigan (upper right); the SARA supercomputer center in The Netherlands (lower right); the Gwangju Institute of Science and Technology (GIST) in Korea (upper left); and, the Korea Institute of Science and Technology Information (KISTI) (lower left). In this experiment, EVL, Michigan, SARA, KISTI and GIST

sent video from their facilities to two 10 Gbps SAGE Bridges at StarLight (which had evolved directly from STAR TAP, mentioned previously), and received only those videos they wanted to receive. For example, while SARA sent its video stream, it chose to only receive streams from EVL and Michigan. The video was lightly compressed (approximately 600 Mbps per video stream), requiring around 2 Gbps to be streamed over TransLight/StarLight to/from SARA. Here one can see there are five rooms "sewn together" over three continents, creating a planetary-scale collaboratory.

Finally, in November 2009 at Supercomputing 2009, Calit2's Jurgen Schulze and Kara Gribskov did a demo reminiscent of the televisualization event between NCSA and Boston two decades earlier. The photo (from Tom DeFanti) is taken in Portland, Oregon on the SC'09 exhibit floor—Jurgen is in San Diego, in the Calit2 StarCAVE [33], a $3m^3$ virtual reality display, and is engaged in an HD teleconference with Kara who is using a ten-panel NexCAVE portable virtual reality display. The videoconferencing HD stream uses commercial LifeSize HD units and the CENIC network is used to interact with the data in three dimensions, which is shown simultaneously on both VR displays. The LifeSize uses 6 Mbps and the interaction, mainly navigation



in this demonstration, is done by low latency/low bandwidth exchange of tracker information, once the models are downloaded to each display's cluster. When the models are updated in any significant way, the data exchange can consume every bit of bandwidth available. To facilitate large data updates and low latency joint navigation, CAVE systems are generally connected by 1GE or 10GE Layer 2 vLANs and use UDP-based transmission protocols to maximize transfer rates and minimize latency, as compared to the 1997 tele-immersion demo which used the shared vBNS Internet.

Summary

This quest for tele-immersion has come a long way in two decades and the dream that fiber optics could eliminate distance on a global basis has begun to come true. There are currently between fifty and a hundred OptIPortals, and a similar number of CAVEs, in use around the world. Many demonstrations are carried out each year over the global OptIPlatform. However, for this new global infrastructure to really take off we dearly need the techno-socio-computer science insights that Alan would naturally give us!

Acknowledgements

The author would like to thank all his colleagues at the National Center for Supercomputing Applications, the National Computational Science Alliance, and the California Institute for Telecommunications and Information Technology for the 25 years of joint work on these ideas. The partnership with the UIC Electronic Visualization Laboratory and the Argonne National Laboratory was essential to the innovations described. Much of the work was supported by the National Science Foundation's Supercomputer Center and PACI Programs, OptIPuter grant, many other NSF and DOE grants, as well as the Gordon and Betty Moore Foundation CAMERA grant.

Larry Smarr was for fifteen years a founding director of the National Center for Supercomputing Applications (NCSA) where he helped drive major developments in planetary information infrastructure: the Internet, the World Wide Web, scientific visualization, virtual reality, and global telepresence.

In 2006 he received the IEEE Computer Society Tsutomu Kanai Award for his lifetime achievements in distributed computing systems. He is a member of the National Academy of Engineering, and a Fellow of the American Physical Society and the American Academy of Arts & Sciences.

Larry is currently the Harry E. Gruber Professor of Computer Science and Engineering at UCSD, and the founding director of the California Institute for Telecommunications and Information Technology (Calit2).

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