Usage Patterns of Wideband Display Environments In e-Science Research, Development and Training

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Abstract — SAGE (the Scalable Adaptive Graphics Environment) and its successor SAGE2 (the Scalable Amplified Group Environment) are operating systems for managing content across wideband display environments. This paper documents the prevalent usage patterns of SAGE-enabled display walls in support of the e-Science enterprise, based on nearly 15 years of observations of the SAGE community. These patterns will help guide e-Science users and cyberinfrastructure developers on how best to leverage large tiled display walls, and the types of software services that could be provided in the future.

Key words—tiled display wall, immersive analytics, visualization, human centered computing, computer supported cooperative work

I. INTRODUCTION

SAGE (Scalable Adaptive Graphics Environment) [9] and its successor SAGE2 (Scalable Amplified Group Environment) [15, 25] are today’s de facto operating systems to manage Big Data on large tiled display walls (generally called wideband display environments), enabling users to collaborate locally and remotely, and to access, display, share and manipulate documents and visualizations [14]. SAGE’s ease of use makes it an excellent platform on which to display a variety of related, high-resolution information, enabling collaborators to reach conclusions and make decisions with greater speed, accuracy, comprehension, and confidence.

This paper briefly introduces SAGE’s capabilities and user community, and documents prevalent usage patterns in support of the e-Science research, development and training enterprise.

We hope it serves as a guide for new SAGE users to understand how to best leverage SAGE’s capabilities to support the various phases of the e-Science enterprise, as well as a means to stimulate cyberinfrastructure researchers and developers to develop new end-user services for use on wideband display environments – which are fast becoming a standard in universities, national laboratories, companies, and non-profit organizations.

II. THE E-SCIENCE RESEARCH, DEVELOPMENT AND TRAINING ENTERPRISE

Great progress is being made in the development of Workflows and Gateways (such as Jupyter Notebooks and Agave) to support scientific analysis [7, 20]. While these are crucial to e-Scientists, there is also a need to provide broader end-to-end support of the scientific enterprise that involves the “human in the loop.”

Figure 1 summarizes the kinetics of the scientific research, development and training enterprise based on our years of experience researching, developing and deploying cyberinfrastructure tools for domain scientists.

The Phases include: (C) conceptualization/hypothesis generation, (W) data collection and wrangling, (V) visual analysis, (X) knowledge crystallization, and (P) knowledge presentation. Workflows and Gateways primarily fall under W & V. However, research, development, and training frequently transition between all phases, alone or in groups, particularly in the early phases as a result of many micro-failures before achieving and reporting success in X & P. SAGE is being used to support collaborative work in all of these phases, as we will elaborate in the following sections.

III. SAGE AND ITS COMMUNITY

SAGE has become the community standard for cyber-enabled, data-intensive, visual analytics and collaboration. The SAGE project started in 2004, and in 2014 we introduced SAGE2, a web-based system. Since then there have been 5,676 downloads of the SAGE2 server, and approximately 1500 weekly end-users installing the SAGE2 plug-in that is required to connect to the servers. We estimate there have been over 600 administrators in charge of wall deployment in over 16 countries, with an estimated hardware infrastructure investment of $120M. Table 1 lists the 100 most recent installations, where each installation, or site, has many users.
A 2017 community survey showed that the institutions were 67% from academia, 11% from government labs, 9% from industry and 13% other. In this worldwide community, 61% of the sites managed one tiled display wall, and 39% managed more than one. 77% of those who responded to our survey said their walls were used several times a week, with 20% using their walls as often as several times a day. Meeting sizes ranged between 2 and 200, with 20 being the average. Furthermore, the disciplines that use it include: Archaeology, Architecture, Art, Atmospheric Science, Biology, Chemistry, Civil Engineering, Communications, Computer Science, Education, Geoscience, Health, Library Science, Mathematics, Medical, Meteorology, Network Engineering, Neuroscience, Physics, Psychology, and Statistics.

Users treat SAGE display walls as collaboration canvases on which to juxtapose and manipulate a variety of data types and visualizations to help discover underlying trends. For example, users can spread time-series data over an entire display wall, with each visualization depicting a timestep, or they can stream large-scale visualizations from supercomputers and video conferencing systems to the wall to support distance collaboration. These are but some of the features that make SAGE a leading technology for harnessing the data revolution.

SAGE’s widespread adoption resulted from rapidly decreasing hardware costs (a SAGE wall can be constructed with as little as $10,000 today compared to $500,000 in 2004); growing numbers of web applications that interoperate with SAGE2 (e.g., Jupyter Notebooks, ParaViewWeb, Google Docs and Hangout, ARCGIS, PubMed, VTK.js); a community-driven App Store [27, 28]; a library of training resources.
individual progress in the project and form an overarching analysis phase, group members may meet to present their individual work, prompting the colleagues to contribute ad-hoc ideas for future work and testing. For that purpose, a scientist may expose their scripts or filters for the group’s use.

Intensive Writing: represents work that requires large amounts of writing, such as generating reports, memos, or publications.

Intensive Coding: represents work that requires large amounts of computational writing, such as, creating scripts using Python or R, to clean and complete the data or analyze it. Coding is an inherently iterative process and can consume time and computational resources.

The following sections explain how these activities are employed within each of SAGE’s five usage patterns. Note: while not explicitly depicted in Figure 1, SAGE has two overarching patterns, Collaboration and Security, which we will also elaborate on in the sections below.

B. The Conceptualization Pattern

Early conceptualization of research through freeform brainstorming can leverage SAGE’s sticky note tool (digital Post-It Notes created in free text or Markdown syntax). Traditional brainstorm meetings often use paper Post-It Notes – not digital Post-It Notes on display walls. The advantages of the latter are manifold. For example: paper Post-It Notes do not adhere well to poster boards, especially when the Post-Its are frequently moved, and after a brainstorming session, notes on paper Post-It Notes need to be recorded – either transcribed into another document or photographed. Digital quick notes, however, do not suffer from these limitations. In SAGE, display walls with electronic quick notes can be saved in their entirety and subsequently recalled. The notes can also be coalesced into a single text document, which affords the opportunity to generate real-time Word Clouds that summarize the topics posted. At location sites with multiple SAGE walls, a “spare” wall can be used as a permanent idea wall that evolves over time.

One particularly effective SAGE-based approach to brainstorming consists of the following steps: (1) a group of participants use their laptops to independently generate quick notes and post them on the SAGE wall; (2) after some time (e.g., 30 minutes), each group member reads all the notes on the wall and writes a short summary or opinion of what has been posted; (3) all members tile their summaries across the wall and briefly read their notes to the entire group; and, (4) all members then openly discuss what they have just heard.
This methodology has the benefit of giving everyone in the room a voice in the process of ideation. The wall enables them to externalize their thoughts at their own pace and voice their opinions about what has been shared. Each note can contain the author’s name or be made anonymously, freeing the discussion and enabling shy users to participate equally. This is particularly valuable when the native language of a participant is not the dominant language.

Scheduling is another common task in both research and industry, which requires relatively small groups to collaborate and negotiate in order to solve a large logistical problem with many nuances. For scheduling large conferences, the process is traditionally a manual procedure performed using physical tools, such as whiteboards and Post-It Notes, and can take days. The SAGE2 application StickySchedule [8] is a multi-user application for display walls that better enables groups to organize conference schedules. Through authentic use cases with expert feedback from organizers who are heavily involved in large conference scheduling, we validated the usefulness of SAGE and StickySchedule in the collaborative and competitive aspects of conference scheduling, in both collocated and distributed settings.

Another brainstorming task is project planning. For example, Caterpillar periodically plans and schedules project planning meetings for the design, development, engineering and manufacturing processes of construction equipment with worldwide teams and suppliers. These sessions are extremely complex and currently performed manually with paper and Post-It Notes. We worked with Caterpillar to explore the use of SAGE to automate the process [30, 16].

C. The Data Collection Pattern

Data collection typically occurs in the early stages of an e-Science enterprise. The major aspects are identifying available information, inspecting them for quality (through visualization), and planning for future data gathering expeditions. An excellent example is demonstrated in the University of Hawaii C-MĀIKI project. C-MĀIKI (Center for Microbiome Analysis through Island Knowledge and Investigation) scientists study microorganisms in Hawaiian ahupua‘a (ridge-to-reef) to better understand the impact of Earth’s microbial communities on biosphere sustainability. Given the difficulties of reaching the terrain from which microbiome samples are selected and limited resources, there is a critical need to optimize sampling efforts.

C-MĀIKI intends to plan, design and execute experiments over difficult terrains (some of which are reachable only by drones), necessitating the use of SAGE. Scientists will be split into field and lab groups. The lab group will use SAGE to view an interactive high-resolution 3D model of the terrain created from a previous drone flight. The field group will fly a drone and its footage will be streamed to the SAGE wall in real time along with the drone’s current location. The lab group will be able to bring up images from past and current flights, assisted by automated image analysis and stitching, and discuss differences and identify points of interest before sending coordinates back to the field group to collect data.

D. The Data Analysis Pattern

The best way to leverage SAGE display walls is to use their large, high-resolution screens to juxtapose and view a variety of data and visualizations simultaneously, without having to swap between windows on laptop displays. Data analysis involves identifying data or pieces of data with relevant information to the topic at hand, noting trends, and evaluating alternatives. In particular, it enables multiple users to pursue multiple investigations simultaneously, enabling them to consider more scenarios in a given time [18].

This usage pattern is particularly effective for collaborators working together using Computational Notebooks. Computational Notebooks are windows to large-scale computational resources and provide users with a
medium for exploratory and explanatory analysis, with JupyterLab becoming the de facto standard across industry and research [Perkel18]. However, users often remain isolated from one another when using these notebooks. While SAGE walls can provide users with a high-resolution analysis workspace, the traditional linear notebook format does not fully utilize the afforded “space to think” [1]. By extending JupyterLab to interface with SAGE, users can synchronize analyses in their notebook with visualizations on the SAGE large display wall. This supports parallel, juxtaposed analyses produced using a remote, scalable computational resource pool. The following photo illustrates three data analysts using SAGE in conjunction with JupyterLab. Two users work natively in their computational notebooks, displaying their notebooks and visualizations in the shared group workspace while the third manipulates and semantically organizes the information to further support analysis. The SAGE wall content includes one analyst’s shared laptop display, two JupyterLab Notebooks, and five visualizations produced from analyses.

Another example of the data analysis pattern is exemplified by neurobiologists who are striving to identify mechanistic biological models of cognitive processes in the brain (in other words, to understand how we think and how our brain works).

Collaborations among experts in such diverse fields as neurobiology, neuroanatomy, neuroimaging, computer vision, signal processing, dynamic systems, machine learning, and data visualization will enable them to study diverse data flows from animal subjects and make biologically plausible interpretations of dynamic functional neural circuits involved in decision making. As researchers scale and optimize their workloads, SAGE helps them access, share, compare and discuss dynamic brain models of recorded populations. The following photo shows data streams corresponding to various stages of a data mining pipeline from raw data on the left (video of a neurobiological experiment in which a mouse performs behavioral tasks in virtual reality) to an extracted 3D temporal dynamics map of activated neuronal populations (real-time correlogram of all recorded neurons) in the middle section, to reconstructed live dynamics of functional connectivity of the brain circuits on the right.

E. Knowledge Crystallization Pattern

After data analysis comes knowledge crystallization. While data analysis reveals the most relevant data and methods to support the investigation at hand, knowledge crystallization seeks to solidify the linkages among the disparate pieces of evidence in order to draw conclusions. Given the ever increasing size of data, there is a need to create innovative, interactive environments that facilitate the analysis and interpretation of data. This pattern helps address challenges facing researchers and decision makers from all domains, in the creation of data-intensive workflows that bring together different information.

An example of such a workflow is exemplified in SAGE-RDI (River Disaster Information), a SAGE-based tool to enhance a publicly available website in Japan [26] for monitoring river levels, to enable decision makers to arrive at decisions about potential flood events during heavy rainfall with greater speed and confidence. SAGE-RDI [12] was built to take advantage of wideband display walls by embedding meaning into location [1]. At the center of SAGE-RDI, the Japanese government’s web portal is displayed on the SAGE wall surrounded by visualizations showing more detailed information about nearby sensors in a region. Predictable clustering of information is observed to encourage familiarity and hence aid the speed of understanding. Future research will attempt to automate the clustering process by understanding how various placements of information affect user cognitive load on wideband display walls. This layout was useful to determine how an area was doing as opposed to the original format, which only allowed viewing a single sensor at a time without context of where the sensor was located on the map.

Today it is not uncommon for the writing of research proposals and papers to be collaborative endeavors that require the use of shared word processors such as Google Docs or Microsoft Office 365, spreadsheets for budgets and charts, and live video conferences with collaborating partners. The wideband screen estate affords the juxtaposition of all these elements simultaneously so that a more accurate and compelling story can be told. For example, in Figure 1, the picture used for Knowledge Crystallization (X) is the meeting held to discuss the writing of this very paper. Participants in Chicago, Oahu, and the Big Island of Hawaii all connected via SAGE using appear.in for video conferencing and were able
see and speak with each other and simultaneously view the conference website, and examine prior written documents to identify components that would apply to the new paper. Early PDF drafts of the entire paper can also be tiled across the entire wall between collaborating sites for co-authors to see both the detail in the paper in relation to the whole. In general, as part of knowledge crystallization, notes are used to represent the important or critical knowledge to take away from the information reviewed. In addition to heavy note usage during the Conceptualization phase, notes perform a critical role during the Knowledge Crystallization phase as a medium for all participants to identify and confirm relevant knowledge with each other. This is a capability also built into SAGE-RDI.

F. The Knowledge Presentation Pattern

The SAGE display wall is an excellent medium for storytelling through the use of images, text, videos and visualizations. The walls are frequently used as part of tours of a facility, such as a research lab. Increasingly, the walls are replacing traditional whiteboard/blackboard classrooms, and frequently they are used for conference and museum demonstrations, which may require them to be portable.

At the University of Illinois Hospital, a large interactive visualization of Intensive Care Unit (ICU) data for effective patient care handoffs was developed [35]. One of the significant challenges of patient care transitions in ICUs is the lack of effective support tools for outgoing clinicians to find, filter, organize, and annotate information that can be effectively handed off to the incoming team. Using SAGE, a large display, interactive, multivariate, visual approach, aimed towards supporting clinicians during the transition of care, was developed based on observation sessions and interviews with several biomedical researchers and ICU clinicians. It is designed as a scalable, interactive visual approach that supports both overview and detail views of ICU patient data, as well as anomaly detection, comparison, and annotation of the data. Feedback from domain experts indicates this approach successfully meets the requirements of effective care transitions.
Using SAGE, multiple potential solutions can be easily compared, and evolution over time is easier to see, as shown in the following data visualization class at the University of Hawaii at Manoa where students were asked to compare their approach to visualizing data of the 1854 London Cholera outbreak.

SAGE allows the instructor to structure the modules so the students can, not only view the instructional template, but also share and explain their results to the class by presenting their material interactively and in real time. Student feedback has been exceptional, as they enjoy having control of the SAGE wall to present material, which encourages them to apply skills learned in the modules. The students can complete exercises and then subsequently mine data online and run new analyses, and ultimately discuss results with the class. The short presentations they give when sharing their results with SAGE helps solidify the concepts covered in class and improves the overall educational experience. Without SAGE, the course would consist of simple lectures with the instructor presenting all the information. This “one-way” transfer of information limits the ability of the students to practice the skills they are learning in class. Engaging the students with SAGE enhances their learning while simultaneously exposing them to the value of interactive data science tools.

In all the scenarios outlined thus far, there is a need to prepare the visual elements ahead of time. SAGE provides the notion of sessions which enables all content on the wall and their layout to be recorded for later recall. In addition, a collection of content (PDF files, images, videos, etc.) can be packaged into an archive file (zipped folder) and dropped onto the wall for staging before the meeting or, alternatively, can be opened right away and laid out on the wall.

For example: Scott Sellar used SAGE and resources at UC San Diego’s Calit2-Qualcomm Institute, to do a remote presentation from Virginia and California to a SAGE wall set up in the SC18 conference research exhibition. He utilized the Nautilus cluster, a Pacific Research Platform (PRP) “GPU Challenge,” to speed up the segmentation process for his weather data [19]. Through SAGE, he was able to simultaneously use videoconferencing, a shared desktop, a shared JupyterLab Notebook, local animations and real-time dashboards in webviews to demonstrate his process and illustrate GPU cluster utilization. SAGE sessions were effective for storing and retrieving these demonstrations.

In a museum setting, SAGE has also been heavily utilized by the University of Hawaii at Hilo ‘IImiloa Astronomy Center, Hawai‘i’s premier astronomy museum. ‘IImiloa’s Executive director Ka’iu Kimura has been supportive of the CyberCANOE and SAGE technologies. SAGE is used for work meetings, public education and outreach by astronomers, and other scientists at nearby observatories. At ‘IImiloa’s 13th anniversary, the Carnegie Airborne Observatory (CAO) lab used SAGE to showcase their high-resolution land survey scans of areas on the Big Island to the public.
Work has begun to build this security model starting with the incorporation of OpenID Connect (OIDC) into SAGE. OIDC is an integrated identity and access management platform for science, combining federated identity management (Shibboleth, InCommon) with collaborative organization management (CManage), which lets users participate in SAGE sessions through a single sign-on mechanism. Our goal is to extend this robust identity management system whereby user credentials from a single sign-on will be used throughout a session to grant access to various resources (i.e. to retrieve a dataset, start a computation, launch a workflow on remote resources).

VI. SAGE COLLABORATION PATTERNS

Use patterns that affect a large group of collaborators, such as knowledge crystallization and knowledge presentation, can engage users that are either colocated or remote. SAGE enables bridging the gap between a variety of domain specialties where the users are not necessarily physically available to each other.

When collaborators share the same workspace and have access to the same SAGE display, they benefit from shared context and a large “space to think” [1]. Most of the scientific patterns we reflect on in this paper were described with local collaborators in mind. In addition, SAGE is greatly advantageous for remote collaboration as well.

Collaborators at one SAGE display site will commonly work with remote colleagues who have their own SAGE display wall. Different sites often have different physical configurations: for example, one site may have eight screens arranged in two rows, while another has three large displays side-by-side. SAGE allows collaborators to share content between the sites, which can be screen-sharing sessions, PDF documents, images, videos, notes, websites and other applications. SAGE synchronizes their content while giving each site control over the position and size of the content. Local users’ pointers are shared with the remote sites, so a user can point to an element in a webpage or PDF, letting everyone follow the flow of the discussion.

Since SAGE runs on web technologies, we are able to take advantage of online services, such as video conferencing (BlueJeans, Google Hangout, appear.in, etc.), and online editors (Google Docs, Microsoft Office 360, Overleaf, etc.). The benefits of using these services on top of SAGE are the synchronization of content beyond sharing a screen or a camera feed between locations. For instance, when sharing a PDF document between remote SAGE sites, participants at either location are able to control the page being viewed, the number of pages, and use the SAGE pointer to direct everyone’s attention. This makes sure everyone is literally “on the same page.” Extensions to these collaboration patterns are being explored, such as shared partitions of one’s wall (each content dropped into a designated region of the display wall is automatically shared), whole wall mirroring (every window is shared and scaled to fit the remote site physical screen layout), and adapting to the remote participant ‘on-the-go’ (user with a phone or laptop only) to follow a meeting and watch the remote walls without needing a large display.
VII. CONCLUSION & FUTURE WORK

This paper describes how SAGE’s support of the kinetics of the e-Science research, development and training enterprise can be characterized by a number of prevalent usage patterns and tasks that occur within those patterns (Figure 1). These patterns can be used to help e-Science users better leverage SAGE’s capabilities as well as understand how to better use wideband displays in general.

Perhaps most evident from these patterns is that they are effective because they fully leverage the screen estate of wideband display environments—enabling users to distribute information on them in a variety of ways that make it easier for them to see the “big picture” in their data. This then raises the question, once the information is laid out across the wall, is that enough? As the scale and complexity of science and its data continue to grow exponentially, simply being able to present all the information will not be enough. Humans will increasingly need an artificially intelligent assistant to assist with collaboration in the e-Science enterprise.

In the past year, the SAGE team has been considering the design of SAGE3. In SAGE3, the “S” in SAGE will stand for Smart to emphasize its use of AI. For example, SAGE3 will introduce the notion of SmartSpaces—templates that help teams quickly and intuitively initiate common SAGE usage patterns. SmartSpaces will be shareable across platforms, made portable through containerization, and leverage new back-end resources to enable data provenance, recovery, and consistency. Furthermore, the moment documents or data are deposited on the wall, AI will autonomously begin to act upon them. These capabilities will be enabled in SAGE3’s Foresight Engine, which will operate under user-defined rule sets and state-of-the-art machine learning theory, grounded in recommendation systems and reinforcement learning algorithms. The module will be scaffolded atop a lightweight micro-services architecture using existing machine-language libraries (e.g., TensorFlow, PyTorch) to provide AI capabilities. Generated insights will be delivered, in accordance with SAGE’s human-in-the-loop model, to users who will take over from machine learning to interpret what patterns mean and determine if there is any scientific value. These interactions will be recorded and used to reinforce learning and support/justify future decisions. SAGE’s Foresight Engine will bring us one step closer to our ultimate vision of making SAGE a first-class partner in a scientific collaboration [32].

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