Architectural Research in Information Visualization: 10 Years After

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As our civilization dives deeper into the information age, making sense of ever more complex and larger amounts of data becomes critical. This article reports on interdisciplinary work in Information Visualization addressing this challenge and using architectural expertise as its main engine. The goal of this research is to significantly improve real time decision making in complex data spaces while devising a new architecture that responds to complex information environments. Although we have been reporting in aspects of this work for the past 7 years, this paper covers unpublished knowledge, design methods, operational strategies, and other details that bring together all the material published by our group thus far into a comprehensive and useful whole. We conclude by presenting our latest InfoVis design work in Network Security.

BACKGROUND

Until early 20^{th} Century, scientific and engineering decision-making depended on direct human observation of empirical phenomena. Although instruments extending human perception and action had been developed and used, a first hand human involvement in the observation, collection and analysis of information was inescapable. During the past century the extraordinary development of technology made our instruments so potent and ubiquitous that they now largely mediate our relationship with reality. Paradoxically, these very instruments have now evolved to such an extent that they themselves have become too complex, too large, too small, too far away and/or too fast to allow for unassisted human operation. We need instruments to run our other instruments! In other words, doing science or engineering means to work through representations displaying data gathered by sensors which measure essential functions of the particular system in use and/or under scrutiny - think of genetic research, astronomy, quantum physics, medical probing, electrical power plant management, financial trading, weather forecasting, etc.

Thus, as we speak, millions of scientists across the planet are conducting millions of experiments, tests, and analyses in uncountable fields and generating terabits of data waiting to be interpreted. The situation of other decision makers is similar. Every minute, high ranking personnel must go through ever growing amounts of data in order to run factories, computer networks, oil refineries, business transactions, military operations.

More worryingly, the production of data and technology in all areas is accelerating so rapidly that it has outpaced our capacity to manage it [1-4]. In other words, our tools have developed to a much larger extent than the representational instruments necessary to make sense out of what our apparati are finding and doing [5-8] So, here is the problem: there is too much information that is too complex, accumulating too fast and changing too quickly to have much hope of understanding, let alone making use of it [9].

DECISION MAKING WITH MULTI-DIMENSIONAL REAL-TIME DATA

Given this background, it is easy to understand why making quick and accurate decisions in complex and rapidly changing information environments is a major concern in many fields. Given a natural or artificial system, events occur over time that needs to be:

- detected,
- diagnosed, and
- treated.

in order to maintain or improve the "health" of such a system (health being defined as normal or expected behavior).

Current methods for presenting abstract data (e.g., heart rate, stock price, network traffic volume, a reactor's temperature and pressure) in real time are waveforms, pie charts, diagrams, icons, matrices, trees, graphs, etc. Sifting and integrating through screens full of raw data and traditional non-intuitive visualizations produce information overload instead of insight and decision-making power [4, 8, 10]. See Figure 1.

◀ Figure 1: A traditional Anesthesiology display (Hewlett Packard, Photo by Julio Bermudez) is a good example of the current paradigm of real time data representation. Shortcomings include (1) not grouping of variables in cardiac and pulmonary sub-systems, (2) providing no priority and hierarchy to variables, (3) recognizing no functional relationship of variables, (4) color and other design attributes serve no particular meaning, and as a result (5) experts (i.e., anesthesiologists) have the cognitively demanding and error-causing task of associating the variables in real time to correctly diagnose clinical scenarios.

There is clearly a need for new information representations that augment human ability to use abundant data to:

- make more accurate decisions,
- decrease response time,
- reduce cognitive fatigue,
- reduce training time.

Many fields are still using data representation designs of the pre-digital era to monitor systems processes, and there is little innovation in intuitive and interactive audio-visual representations.

STATE OF THE ART IN SCIVIS AND INFOVIS

Alternative methods of information representation exist and are used. Such methods are the offspring of 25 years of research and work in two domains: Scientific Visualization (SciVis) and Information Visualization (InfoVis). In general, SciVis research focuses in data presentation with spatial or formal reference (e.g., oxygen concentration in certain brain areas). In contrast, Information Visualization (InfoVis) addresses representations of abstract information, that is, data that have no specific formal or spatial nature such as pressure, temperature, price, etc. [8, 11-16]. The performance successes of SciVis and InfoVis methods have not been the same. Generally, SciVis has fared far better than InfoVis. The reason may be partially found in the dramatic improvements in hardware power and software sophistication leading to effective techniques and efficient algorithms for volume rendering. This has allowed the solution of many important scientific problems with complex and large scale computational model [17-20]. Another important reason behind SciVis success is that it doesn't usually rely on visual metaphors and other design intensive solutions. As a result, researchers (by and large scientists and engineers) focus their efforts in work directly related to their area of expertise (science and engineering) and therefore more likely to solve satisfactorily.

In contrast, InfoVis must fundamentally come up with visual entities that express abstract data in ways that are easy to recognize by users. Because this is essentially a qualitative task, it resists the quantitative types of approach that, in general, are behind many of SciVis accomplishments. Instead of unleashing creativity, this difficulty has pushed InfoVis work to play safe by applying or improving well known visual metaphors to solve problems. For example, much literature focuses on all derivatives of graphs and trees. Although such techniques are effective and versatile in some cases (i.e., tree maps have proven a wide range of applicability and elegant solutions), they tend to work better for experienced than for inexperienced users and often not so well or not at all when InfoVis needs exceed very basic expectations. Second, most work in InfoVis involves data discovery (i.e. finding insight in large datasets and databases) and not data presentation methods: little literature is available on real-time decision making [21-24] and related work in Defense and Intelligence is mostly classified. Third, InfoVis work has tended to be simplistic, visually naïve and/or highly academic and fail to address real InfoVis demands of real users confronting real time and complex data representation problems. For instance, present InfoVis methods have limitations with scaling amounts of information, and tend to ignore the influence among different data (see Figure 1). Fourth, few examples of successful InfoVis efforts involving the normal full-circle from concept development to implementation and evaluation exist. Fifth and last, most self-defined 'interdisciplinary' InfoVis efforts comprise narrow multi-disciplinary alliances restricted to the hard sciences that rarely include the humanities, art and design as equal partners. Many of the shortcomings of the existing InfoVis paradigm can ultimately be found in this narrow perspective [25].

COMPLETE INTERDISCIPLINARY INFOVIS WORK

Our research group, CROMDI (Center for the Representation Of Multi-Dimensional Information - www.cromdi.utah.edu), was created and operates upon the conviction that the solution to today's information crisis is found in developing what we call a ***new data representation architecture***. We define *data representation architecture* as the organizational, functional, experiential, and media-technological order defining the interaction between data, representation, and user.

Developing such data representation architecture means to offer a new way of approaching InfoVis that, in turn, requires addressing many intertwined issues and dimensions surrounding data presentation. Not only must one have some cognitive model of the user's data-driven decision making process, but also determine the nature and behavior of the data (structure, process), the type of problem, needs and requirements, the technology to deliver such depiction, evaluation systems, etc. Clearly, any one domain alone cannot do this. In fact, this task would overwhelm any single discipline by its sheer complexity, scale, multi-dimensionality, etc. Nothing less than a well-organized interdisciplinary approach will do. Bringing together the expertise of different disciplines provides the necessary tools to solve these complex problems.

We coined the term '***complete interdisciplinarity***' to indicate the involvement of all the disciplines that are *necessary* and *sufficient* for the beginning-to-end solution of an InfoVis problem [25]. This means a very wide and diverse collection of fields encompassing the sciences, the humanities, and art and design. For nearly 10 years, CROMDI has been consciously applying complete interdisciplinarity by bringing together faculty and researchers across the University of Utah campus (in Salt Lake City, USA) and beyond to work in InfoVis problems. Our group includes experts from Architecture, Bio-engineering, Business, Communications, Choreography and Dance, Defense, Computer Science, Mathematics, Medicine, Music, and Psychology.

In addition to 'complete interdisciplinarity', there are two practices that set our work group apart from others in the InfoVis community:

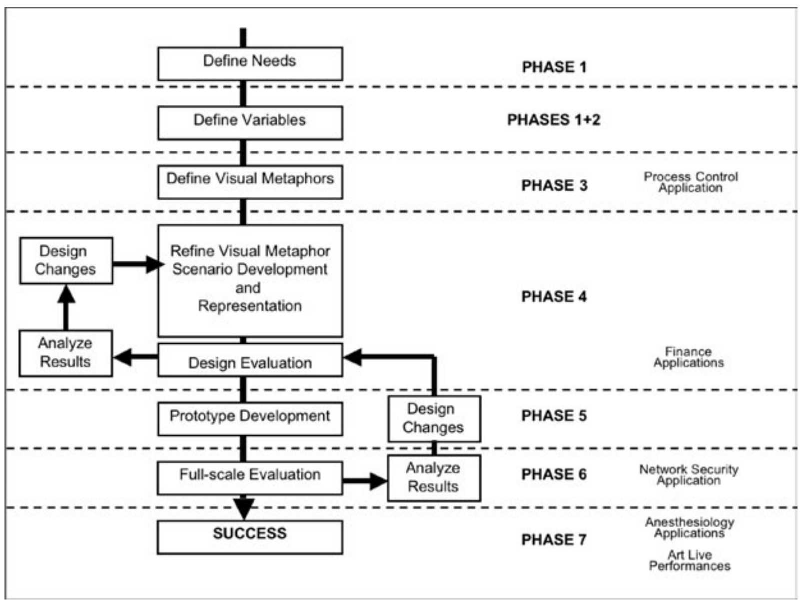
1. The utilization of the *design process* as the basic engine behind our interdisciplinary methodology, and
2. The application of *systematic evaluations* throughout the whole process to feedback directly into the design process.

Since we have discussed both practices in some detail elsewhere [25-30], this article will next describe the interdisciplinary structure supporting CROMDI's work and the design phases involved from problem definition to data analysis and mapping, to implementation.

INTERDISCIPLINARY STRUCTURE AND DESIGN PHASES

Collaborative success is ultimately grounded in the careful structuring of a team's group dynamics, which are based on clear roles, respect, trust, values, shared goals, and a common language [31-34]. Accommodating different methods, techniques, positions, interests, standards, idioms, perspectives, knowledge, expectations, etc. of people from different disciplines takes considerable time and effort as one has to overcome prejudices each field has of the others [35-36]. The essential trust among different disciplines only becomes real after each field has demonstrated through their work their value. A main reason why CROMDI continues to work is because we have been very aware of the human aspects behind our research job, often engaging in painstaking efforts in dealing with what may seem as irrelevant if not annoying personal situations. And yet, we are firm believers that it is in these 'personal' matters where all relationships either succeed or fail, and where more often than not the very existence of our group hinges. If one is not ready to have this sensitivity, then they should not engage in the complex multi-party relationship that is at the heart of true interdisciplinary collaboration. These statements are not a theoretical elaboration. We ourselves have tested each one of them and found them to be true.

What kind of actual interdisciplinary structure can embody and support collaborative practices? Given the size and expertise of our diverse team, the practice of complete interdisciplinarity, the logic of the design process, the build-in evaluation system, and the nature of the challenge, we break down the CROMDI group into several teams, each one addressing the problem from their specialty but in direct collaboration with other teams according to needs. Thus, we have teams in Design, Computer Science, Psychology, Application (e.g., Medicine, Business), etc. Although there are strong roles to play by each of these teams, its is the Design Team who establishes the overall rhythm of the process and is to whom all the other teams interact with at different times. This follows a modality similar to that of the traditional design studio setting. For a discussion on this working practice and its strategies, please see [29].



► Figure 2: Iterative Loops and Phases in CROMDI's InfoVis Design Development Process.

The process of creating, developing, and implementing InfoVis schemes follows a method common to all design activity (Figure 2). First, the problem and the metaphors for the information that will be displayed are defined (phases 1 through 3, see below). Next, an iterative process via "dialogical exchanges" is used to learn and incorporate the feedback from the targeted users (phase 4). New interpretations are discovered and the design is refined. The prototype development moves to full scale user evaluations (phases 5 and 6), which includes a second feedback loop of iterative evaluation for design usability and intuitiveness. In phase 7 we attempt to market the display for commercial use. Our InfoVis work in Anesthesiology has completed phase 7 whereas others are at different points in their development phases. Each design refinement is evaluated and methodically analyzed to elucidate design changes while minimizing designer bias. The goal is to minimize alterations late in the InfoVis design's lifecycle, when changes are more costly (in time, technology, potential litigation, etc.).

More specifically, each phase has the following objectives:

- *Phase 1*: problem definition and data analysis to establish needs, relevant variables and relationships.
- *Phase 2*: organization of variables onto datasets based on functional relationships and needs (identified in the user's mental model):
  - between data within a dataset,
  - between several datasets.
- *Phase 3*: creation and design of metaphors and datasets mapping:
  - onto 2D and 3D objects and spaces and their properties,
  - onto their location in space and time.

In other words, the digital objects and spaces are used as symbols of critical functions of the system, and embed these functionalities:

- interplay or integration among different variables;
- decomposition of variable into its independent components;
- functional relationship among variables;
- discrete versus continuous variables;
- exact quantitative values versus qualitative behavior of variables;
- global behavior of variables (history and trend) versus local (moment and details);
- specific details of the system (micro-scale) versus general state of the system (macro-scale).

For a more detailed discussion on phases 1 through 3, please refer to [12]

- *Phase 4*: usability testing, refinement and re-testing of the scheme until reaching internal and external consensus that the InfoVis design works.
- *Phase 5*: InfoVis scheme coding into software.
- *Phase 6*: final and full-scale evaluation of the prototype, including any necessary minor adjustments.

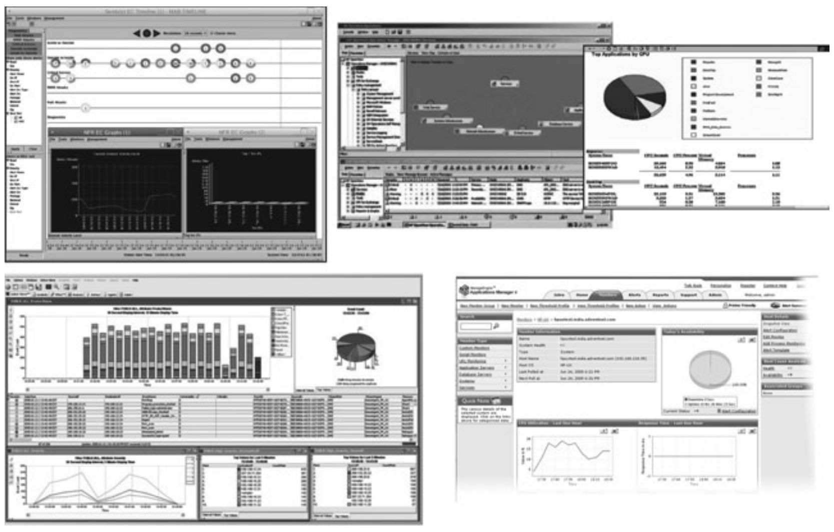
- *Phase 7*: if successful, phase 6 leads to the implementation, deployment, and/or commercialization of the InfoVis design.

These phases unfold using different representation techniques that go from initial ideation to software coding. During the initial part of the project, design ideas are developed and modeled using static representations both in analog and digital media. Still images of these visualization models are used to evaluate the design ideas. Once we have arrived at a model in which experts can recognize variables and functions quickly and easily, we move to encode the model's design into real data-driven animated prototypes (not real time). A series of usability testing evaluations is carried out and the design is reviewed until satisfactory perceptual congruency and apprehensibility results are obtained. Eventually software is written to run the representation design prototype driven by real data in real time. Then testing using high fidelity simulations is conducted to assure that performance is improved in realistic settings.

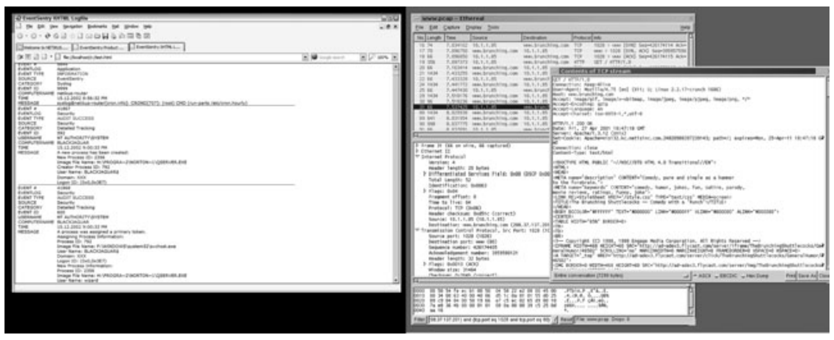
Following we will present our work Network Monitoring & Security. The authors have reported their InfoVis research in Anesthesiology, Finance, and Live Art Performance elsewhere [5, 12, 25-30, 37-44]

INFOVIS DESIGN WORK IN NETWORK MONITORING AND SECURITY

The health and security of information networks is a priority for science, engineering and society today. The Network Operations environment is not as regulated as Anesthesiology, and is an ever changing environment with new threats and problems that are constantly emerging. These facts have precluded the codification of heuristic knowledge, coherent analysis methodologies, and the standardization of monitoring tools. In a typical situation, a single engineer is responsible for a network, chooses among a plethora of software that substantially vary in purpose, complexity, and price, customizes a dashboard, and learns while working. Although countless tools have been developed to visualize the hierarchy of data structures (for instance, see Figure 3), there is still no good information visualization model that adequately presents the extensive data volume that needs to be depicted while reducing its complexity without obscuring important data [45-48]. For this and other reasons, network managers by default end up monitoring the health status of their assets through text-based or spreadsheet report screens (Figure 4). However, given the scale, complexity, and continuous change of the data involved, it is practically impossible for users to follow up the situation of their systems and networks using such InfoVis methods. The result is the reactive management of problems and the consequent down time, loss of data and productivity, unpredictability, insecurity, and worse.



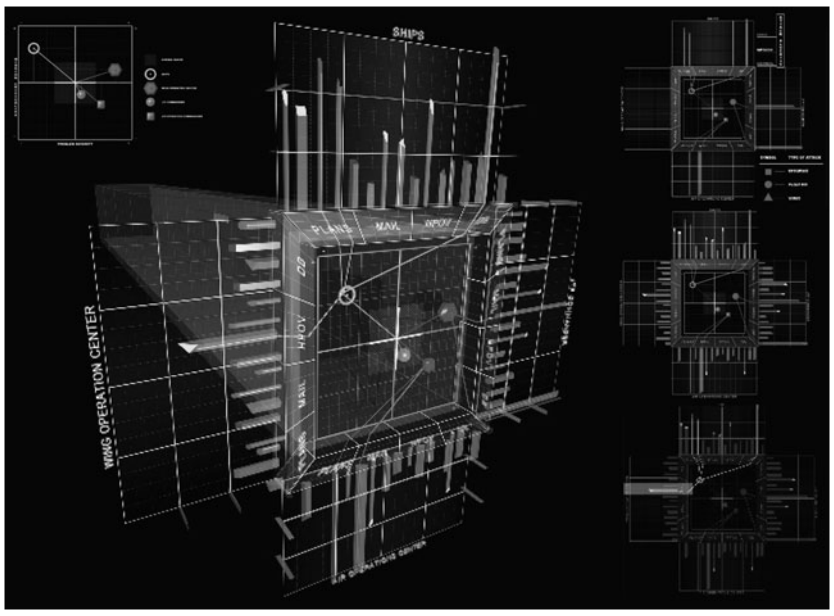
◀ Figure 3: Current Visualization Models used in Networking Monitoring. *Top left*: Sensivist (from Genesis Communications, http://www.genesiscom.ch/en/ 15/04/2006). *Top right*: HP OpenView 7.5 for Windows (from Hewlett Packard, http://www.managementsoftware.hp.com/products/ovowin/index.html 15/04/2006). *Bottom right*: HP-Unix Monitoring (from Hewlett Packard, http://manageengine.adventnet.com/products/applications_manager/hp-unix-monitoring.html 15/04/2006). *Bottom left*: Sentinel (from Novell's e-security, http://www.esecurityinc.com/Software/Products/Control_Center.asp 15/04/2006)



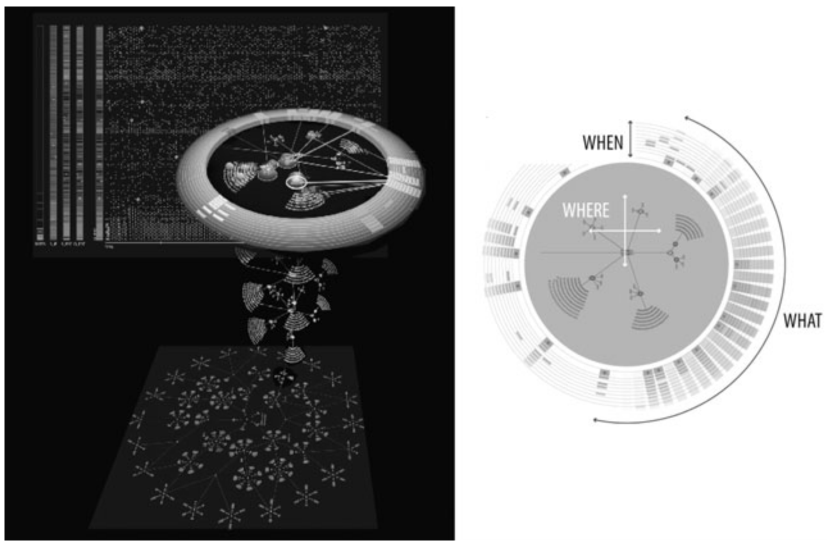
◀ Figure 4: Text-based and spreadsheet report screens are the most commonly used methods for monitoring the status of computer networks. *Left*: EventSentry, http://www.eventsentry.com/ (15/04/2006), *Right*: Ethereal, http://www.ethereal.com/ (15/04/2006).

Our work takes on this challenge by a combination of synthetic reductions through spatial and temporal data scaling and layering, referential frameworks, and typological and topological data mapping design so that abnormal behavior may be detected.

Before moving to the developed InfoVis design (now in phase 6), we'd like to point to earlier scheme (Figure 8) Although this prototype had many InfoVis possibilities, it was abandoned because of its inability to adapt to increasing levels of information demands place on it by actual data and user needs. Here we'd like to stress that work that doesn't find immediate application is very important because it establishes new ways of interpreting a particular problem space. In addition, such design insights sometimes find their way across fields and applications, For example, we found that, with appropriate translations and reinterpretations, this very scheme could be adapted to address unfulfilled information visualization needs in Oil Refinery process control.



► Figure 5: CROMDI Quadrant scheme for Network Monitoring & Security. This prototype enables the visualization of multiple network zones in which items are displayed in relation to use, type, traffic, security, criticality, and location. Size, color, thresholds, and infrastructure connectivity provide further monitoring insight into the network system. (© copyright 2000-2003 CROMDI, all rights reserved). More information on this prototype may be found in [27].

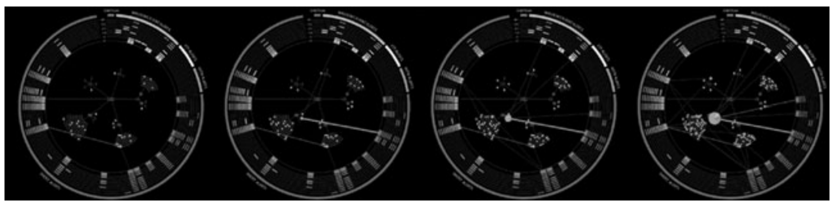


► Figure 6: The w3 Concept (© copyright 2005 CROMDI, all rights reserved).

The Quadrant scheme was developed for a research project that requested an open-ended and visionary exploration of InfoVis solutions addressing general data concerns in Network Security. Three year ago, we used this prototype to lobby and eventually win a major grant to develop a working InfoVis system solving an actual network monitoring and security situation better than using existing data display devices. Soon after starting our design research work, it became evident that our Quadrant scheme was too rigid for the type of data demands and user needs we had to respond to. The result was a significant transformation that led to the creation of the 'looking glass" scheme showed in Figures 6-9. The concept is simple enough: applying an imaginary 'looking glass' tool to zoom in and observe in detail the activity of a particular network in the midst of a vast universe of computer networks (Figure 6 left).

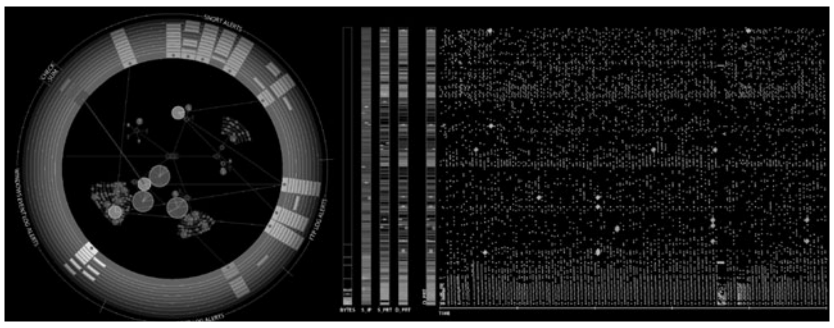
More precisely, and influenced by the earlier scheme, we redesigned the quadrant (4 sides) into a circular form (infinite sides) that although following some of the same data mapping strategies, it underwent important changes. The basic concept (Figure 6 right) became simpler and easier to understand and use: network data events are visualized following a What-Where-When (or "w3") mapping organizational system, The finally developed scheme, called VisAlert (Figures 7-9), is a display that helps network security analysts detect and respond to network attacks and misuse. This is done by first correlating data from network and host intrusion detection systems (IDS) and its attributes represented in two distinct 2D domains, the *What-When* (the ring) and the *Where* (the topology map at the center). In VisAlert, correlation is shown as many-to-one convergence either from the ring to the map, or the map to the ring. Figure 7 portrays an attack scenario as seen in VisAlert, whereas Figure 8 shows, in more detail, the prototype in action with real data.

◀ Figure 7: VisAlert Display left showing normal network traffic. VisAlert Display right showing an intrusion attempt on machine with large circular node. (© copyright 2005 CROMDI, all rights reserved).



◀ Figure 8: Dig-in *(left)*: The attacker places toolkits on the compromised node after discovering the vulnerable service. *Exfiltration (second from left)*: Snort violations indicate data being moved off of the machine. *Migration (third from left)*: Using the internal machine, the attacker searches the network for other vulnerabilities. *Filtered view (right)*: The last stage of the attack showing only machines with two or more different alert types. (© copyright 2005 CROMDI, all rights reserved).

The scheme also includes three separate visualization modules that provide the user with different ways to view network related data. See Figure 9. These visualization modules allow for the visual correlation of different logs from computer systems across an enterprise for the detection and diagnosis of complex intrusion attempts. The first module (w3, "looking glass", on the left) provide a view "at a glance" of the number of different types of alerts associated with machines across a network. The second module (waterfall display in the center) shows a summarized view of the network traffic associated with selected network modes. Both modules in interaction or by themselves, provides the capability to drill down into particular aspects of the data to see patterns over a variable amount of time (third or analytical module, on the right). The user then has the capability to interact with refined views of the data and configure different comparisons in the analysis. These three views can then be saved and compared that may reveal attack signatures. The user also has the capability to enter notes about particular nodes that can be accessed by others as a way of sharing information. In summary, the visualization allows for the following benefits: Data fusion of disparate data sources, data drill down, a holistic view of overall network activity, pre-attentive design that takes advantage of innate human perceptual qualities.



► Figure 9: VisAlert Display showing 3 visualization modules. The leftmost display shows host and network based alerts around the ring and mapped to network topology. The waterfall display in the center shows a summarized view of network traffic associated with selected network nodes. The analysis view on the right shows a detailed view of the waterfall with time expanded in the X dimension. This work is © copyright 2003-05 by CROMDI, all rights reserved.

A major reason for the success of this work has been our direct collaboration with Battelle and the University of Utah central network management. The former provide us with expertise support in high security network operation and technology. The later enabled us to learn from and respond to actual users while permitting us to incrementally evaluate our ideas, prototypes, and technology. This was essential to determine users' cognitive models in the layering, integration, and scaling of data while still allowing high levels of user interactivity as required by actual operation needs and customs of network managers. In addition, direct access to real data, concrete problems, and existing technology made us to focus on practical yet comprehensive ways of addressing the InfoVis challenge.

By offering a viewing device supporting both analytical and exploratory decision making, our data representation architecture presents critical events in ways that are easier to detect, diagnose and deal with [49-52]. Such visualization research effort provides a complementary vision of network operations to the one coming out of many pure Computer Science Network Research efforts. It took 18 months to produce a working prototype responding to real network monitoring data that has the ability to increase users' situational awareness of network security issues [52-53]. At present, we are finalizing the coding of VisAlert into software so that final on site and on demand tests could be performed before commercialization and/or adaptable deployment may be pursued (phase 7)

CONCLUSIONS

As our civilization dives deeper into the information age, making sense of ever more complex and larger amounts of data becomes critical. Our interdisciplinary work in InfoVis responds to this challenge using architectural knowledge, skills, methods, and visions as its main engine. We have recently articulated possible reasons for the special relevance of Architecture in InfoVis [28]. In any case, carrying the interdisciplinary work forward has proven laborious but very rewarding. Succeeding meant to overcome many challenges including:

- Compartmentalized academic structures that do not encourage interdisciplinary work.
- A widespread attitude that working across fields is less scientifically rigorous (or suspect design-wise) and the consequent difficulty in convincing funding agencies, peers, and journal publications.
- Significant disparities in salary, academic recognition, and power among the different disciplines.
- Patience to trade short term ineffective and time-consuming collaborative efforts for long term high productivity and success.

Despite these challenges, we have been very successful at designing, building, testing, and deploying information visualizations supporting real time decision making in Anesthesiology, Finance, Process Control, Live Art Performance, and Network Monitoring. These information spaces display data in a format that makes best use of human natural perceptual abilities. Rigorous scientific testing has demonstrated that dwelling in such data representation architectures allows people (i.e., network managers, traders, anesthesiologists, etc.) to make more accurate, faster, and better decisions than with existing systems [26, 37, 30, 42-44, 53-58]. And they can do so while with reducing their cognitive load, stress, and training time.

The success of this enterprise is proven by the longevity of our group (nearly 10 year long), over $6.1M in royalties, contracts, licenses and grants (from the NIH, NASA, DARPA, ARDA, the State of Utah, and private industry), and a very productive record with 55 articles published in 5 fields, several pending patents, two spin-off companies, 4 commercial licenses, and more than 20 public live art performances in 3 continents. The commercialization of our InfoVis technology in Medicine and its expected soon approval by FDA means that our work will shortly find its way in operating rooms, intensive care units, and other medical environments for the benefits of society at large.

Such accomplishments as well as the role of Architecture in leading this whole interdisciplinary effort educate the university environment of the significant role that Architecture may play in advancing the cause of science, technology, and academia at large. As important, it demonstrates the value of architectural education and inquiry to our own students, practitioners, scholars, and administrators. All things considered, this research in InfoVis expands the existing boundaries of architectural research while offering a valid example of alternative architectural practice. It also shows the potential leadership role that architectural schools and faculty may play in interdisciplinary education and research on campus and beyond.

Acknowledgements

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58. For a much longer account of all the publications related to our InfoVis in Anesthesiology and other related areas, please visit http://abl.med.utah.edu/~infoviz/cv.html#top (15-04-2006)

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