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Secure Collaboration Across the Reality-Virtuality Continuum Using Reservoir Data

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Secure Collaboration Across the Reality-Virtuality Continuum Using Reservoir Data

by

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Abstract

Acquiring, storing, processing, synthesizing, visualizing, and interpreting data are core to scientific knowledge discovery. This data life cycle is common to many diverse fields such as medicine and petroleum engineering. A wide range of techniques may be used for interacting with and visualizing data. Immersive technologies such as augmented reality and virtual reality show great potential to enhance important workplace activities such as collaboration. To this end an immersive, collaborative tool for visualizing reservoir data is discussed. Some collaborative scenarios using these technologies are then described. It is important to carefully consider how these technologies will be incorporated into a professional setting to ensure tools based on these technologies will provide a high quality user experience while meeting the security needs of industry. In order to further this goal, some of the architectural considerations of a collaboration tool that uses a variety of technologies from the reality-virtuality continuum are explored. A prototype tool is then presented that has been developed for collaborating over petroleum reservoir scenarios involving sensitive data. This tool incorporates visual protection mechanisms to facilitate collaboration while providing enhanced control over information disclosure. A user feedback session was performed with reservoir engineering subject matter experts, and the results from this exploratory evaluation are reported.

Publications

Some materials, ideas or figures in this thesis may have appeared in the following publications:

- S. Cartwright, E. Sharlin, M. Costa Sousa, and Z. Chen. Investigating the Effectiveness of Security-Enhancing Visual Protections for Immersive Collaboration. In *Poster Session Proceedings of the 44th Graphics Interface Conference*, GI '18. Canadian Human-Computer Communications Society, 2018.
- R. C. Ramos Mota, S. Cartwright, E. Sharlin, H. Hamdi, M. Costa Sousa, and Z. Chen. Exploring Immersive Interfaces for Well Placement Optimization in Reservoir Models. In *Proceedings of the 2016 Symposium on Spatial User Interaction*, SUI '16, pages 121–130. ACM, 2016.

As a part of my MSc research I have been directly involved in the following projects:

- D. Yuen, M. Santoso, S. Cartwright, and C. Jacob. Eukaryo: An AR and VR Application for Cell Biology. *International Journal of Virtual Reality*, 16(1):7–14, Oct. 2016.
- D. Yuen, S. Cartwright, and C. Jacob. Eukaryo: Virtual Reality Simulation of a Cell. In *Proceedings of the 2016 Virtual Reality International Conference*, VRIC '16, pages 3:1–3:4. ACM, 2016.
- A. S. Nittala, N. Li, S. Cartwright, K. Takashima, E. Sharlin, and M. C. Sousa. PLANWELL: Spatial User Interface for Collaborative Petroleum Well-Planning. In *SIGGRAPH Asia 2015 Mobile Graphics and Interactive Applications*, SA '15, pages 19:1–19:8. ACM, 2015.
- N. Li, S. Cartwright, A. Shekhar Nittala, E. Sharlin, and M. Costa Sousa. Flying Frustum: A Spatial Interface for Enhancing Human-UAV Awareness. In *Proceedings of the 3rd International Conference on Human-Agent Interaction*, HAI '15, pages 27–31. ACM, 2015.
- N. Li, S. Cartwright, E. Sharlin, and M. Costa Sousa. Ningyo of the CAVE: Robots As Social Puppets of Static Infrastructure. In *Proceedings of the Second International Conference on Human-Agent Interaction*, HAI '14, pages 39–44. ACM, 2014.

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List of Symbols, Abbreviations and Nomenclature

Symbol	Definition
3DUI	3D User Interface
ABAC	Attribute Based Access Control
AR	Augmented Reality
CSCW	Computer Supported Cooperative Work
DAC	Discretionary Access Control
FOR	Field of Regard
FOV	Field of View
HLAPI	High Level API
HPC	High Performance Computing
LLAPI	Low Level API
MAC	Mandatory Access Control
MR	Mixed Reality
RBAC	Role Based Access Control
SWFMS	Scientific Workflow Management System
SAR	Spatial Augmented Reality
UI	User Interface
UX	User Experience
UNet	Unity Networking
VR	Virtual Reality
WEP	Workflow Execution Plan
WfMS	Workflow Management System
XR	Extended Reality

Chapter 1

Introduction

Acquiring, storing, processing, synthesizing, visualizing, and interpreting data is core to knowledge discovery. This data life cycle is common to many diverse fields in industry and in academia. However, there are many challenges remaining that must be overcome to provide this life cycle with effective approaches and tools, especially in modern data intensive environments [280]. These challenges include data challenges, process challenges and management challenges. Of particular interest to this work are the management challenges of data and information sharing, privacy, and security. Specifically, a solution must be found that allows data and information to be shared effectively while respecting privacy and security concerns. This solution must consider the data management, access control and user privacy supporting collaborative visualization and analysis of data.

A common method of analysing data is through visual analytics [145] [294]. Visual analytics is a term that was orignally coined by Jim Thomas at the Pacific Northwest National Laboratory and popularized by the work “Illuminating the Path: The Research and Development Agenda for Visual Analytics” [58]. Visual analytics has been defined as the science of analytical reasoning facilitated by interactive visual interfaces [330] [305]. Visual analytics combines computational and visual analysis methods with a tight coupling through human computer interaction in order to gain knowledge from data. Visual analytics represents the cumulation of a variety of techniques over time. For instance in 1973 Anscombe argued the value of visualizing data to assist with analysis [13]. In his 1977 publication ”Exploratory Data Analysis” [313] John Tukey argued the value of using exploratory data analysis (EDA) to discover clues and themes in data, in addition to confirmatory data analysis (CDA). As information visualization became popularized by works such as ”The Visual Display of Quantitative Information” [312], and ”Readings in Information Visualization: Using Vision to Think" [50] the importance of visual methods to explore and understand data became more accepted [146] [147]. The application of visualization to scientific computing problems created the field of scientific visualization [206] [135]. In step with these advances, computer supported collaborative work (CSCW) and groupware emerged and were concerned with improving how people effectively work together supported by computer systems [112]. The merging of these interests ultimately lead to the study of collaborative visualization [130].

When exploring or collaborating over data, there may be very different requirements and complexities depending on the data and the objective of the data exploration. Due to this, a wide range of techniques may be used for visualizing and interpreting data. These techniques may be supported by varied technologies including large displays [19], mobile devices [199], tabletops [272], virtual reality [181], augmented reality [202], wearables [198], hybrid reality [249], and combinations of immersive devices [217]. In 1994 Paul Milgram and Fumio Kishino defined the reality-virtuality continuum [214] as part of a taxonomy of displays including immersive devices. At one end of the continuum is the real environment, comprised of the physical environment and non-immersive devices such as screens. Next along the continuum is augmented reality which superimposes computer-generated images onto a view of the real world, thus augmenting the physical environment with digital artifacts. Augmented virtuality is a virtual environment where real objects such as the users themselves can be merged into and interact with an immersive environment. Finally, virtual reality defines the other end of the scale, where the world consists entirely of digital content. Together these technologies can be applied to support visual analytics. The application of immersive technologies to visual analytics is called immersive analytics [53] [114]. With the increased availability of high quality and low cost immersive devices, it is likely collaboration across all devices in this continuum will eventually become an integral part of collaboration scenarios and support collaborative immersive analytics [32] which combine visual analytics and immersion with computer supported cooperative work techniques. Many scientific fields rely upon collaboration for effective discovery. Collaboration may be either co-located or remote and may use any of these technologies. Data processing may be distributed in order to assist with user experience by improving responsiveness and to combat issues of scale. If sensitive data is used, then methods to protect this data must also be integrated.

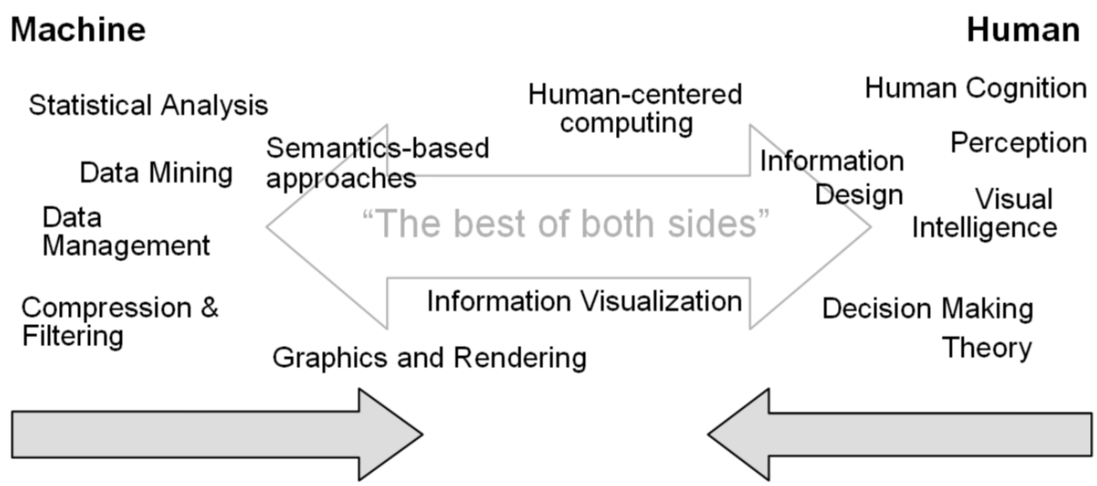

Figure 1.1: Visual analytics uses various disciplines to leverage the strengths of human congnition and computation in an integrated manner [145].

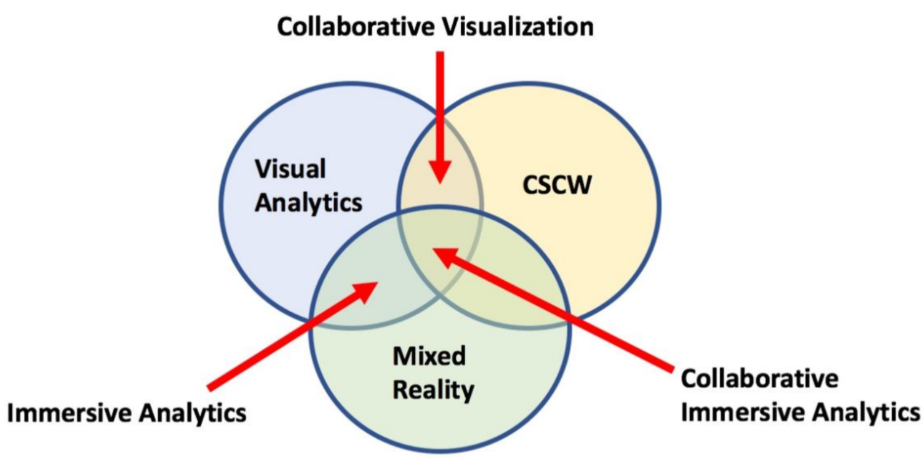

Figure 1.2: The relationship between Collaborative Immersive Analytics, Collaborative Visualization and Immersive Analytics [32].

This work was performed at the Energi Simulation / Frank and Sarah Meyer Collaboration Centre [251]. The Energi Simulation / Frank and Sarah Meyer Collaboration Centre is a visualization lab with a wide variety of hardware including a large scale visualization system based on a CAVE (Cave Automatic Virtual Environment) [61] called a Barco MoVE [25]. The Barco MoVE system has four 8 foot high and 10 foot wide screens (left, centre, right, floor), each with stereoscopic 3D projectors allowing information to be displayed on screens with or without stereoscopic 3D. The Barco MoVE adds two additional configurations to the original immersive cube shape associated with a classic CAVE. In the first mode, the left and right screens may be moved to a 45° angle, providing an immersive theatre for presentations and collaboration. The screens may also be configured to create a large 30 foot visualization wall.

Large scale visualization facilites such as this one have had mixed success in terms of utilization and perceived value across different organizations, and have fallen out of favor in some organizations and even industries. Often these facilies were utilized as passive visualization theatres. Typically most users would observe while a presenter provided context. This kind of usage is at odds with the highly interactive and exploratory nature of applications incorporating modern collaborative visual analytics and immersive analytics techniques. This is likely one of the reasons that such centres have been underutilized in some orgnaizations. Even expensive visualization centres must be equipped with the appropriate software that can enhance workflows and unlock the value of the hardware. The introduction of affordable and high quality virtual reality (VR) head mounted displays (HMDs) such as the Oculus Rift [230] or HTC Vive [122] and augmented reality (AR) HMDs such as the Microsoft Hololens [211] has also provided new opportunities to create immersive analytics applications that may be used in a variety of scenarios and may work in tandem with large scale facilities. This has been the approach at the Energi Simulation / Frank and Sarah Meyer Collaboration Centre. Instead of focusing on passive experiences and visualizations, a variety of tracking technologies such as Vicon tracking systems [317] and Microsoft Kinect sensors [342] have been installed and used to support a variety of interactions and collaborative workflows.

Interactive tabletops, non-immersive devices and even robots have been incorporated into the work at the collaboration centre, with a focus on integration of technologies, collaboration and interaction. Applications are developed to move between head mounted displays and large scale

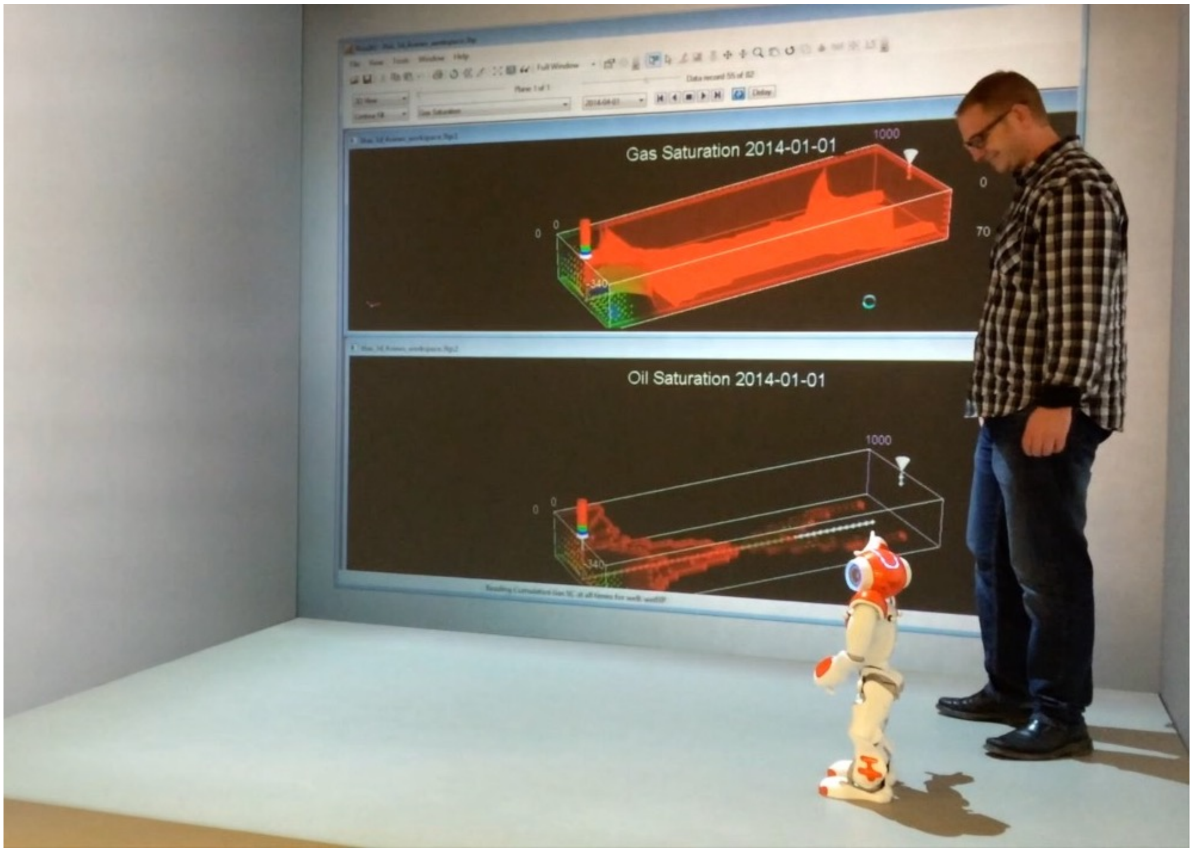

Figure 1.3: Integrating robotic guides with visualization infrastructure [184].

visualization systems. Collaboration and interaction with data, with the unique properties of each hardware platform in mind, are central to increased utilization and value. Rather than providing an immersive data theatre, the Energi Simulation / Frank and Sarah Meyer Collaboration Centre is now an interactive visualization and analysis hub, where users may take data they experience on personal devices, and interact with it together with collaborators, supporting immersive and non-immersive analytics workflows. Providing support for sensitive data is another aspect that is critical to effective use of this technology and will provide value to other visualization centres that work with a variety of hardware in an industrial setting, such as the Petrobras CENPES Visualization and Collaboration Center [200]. This is a centre that has long focused on developing collaborative, immersive tools for the oil and gas industry [80] [238].

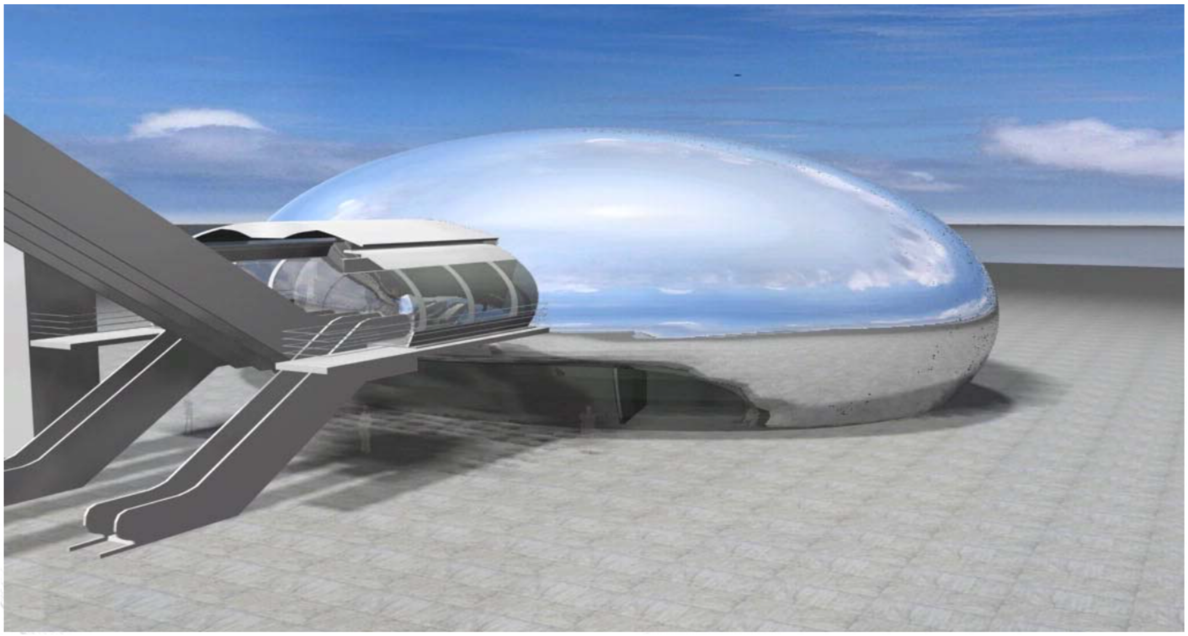

Figure 1.4: Petrobras CENPES Visualization and Collaboration Center (NVC) [200].

1.1 Motivation

As computing becomes more ubiquitious and a wider variety of technologies are incorporated into various scenarios the challenges of data and information sharing, privacy, and security will only become more acute. We are moving towards a converged reality where activities in the ”real world” and those in the virtual world are more tightly integrated [283]. There is a need to understand these scenarios, so that effective management of data and appropriate access control policies and techniques that directly support agile scientific collaboration may be applied. Although technical solutions alone are only part of a greater solution to this problem [260], they are a prerequsite for collaboration. Collaboration is often hindered by concerns over sharing sensitive data. Trustworthy systems that support collaboration are especially imporant in situations involving Strategic Negotiation [74] or coopetition [33]. These are scenarios involving both cooperative and competetive aspects, where users must collaborate, but may not want to reveal all information available during a collaboration. These situations require collaboration tools that support users with different levels of access to the data they are working with. Across organizations, these scenarios are important for mutually beneficial alliances which are needed to cope with faster business dynamics and higher uncertainties. Within organizations, organizational units must cooperate with each other and learn from each other but at the same time compete with each other in many aspects of their business operations [270]. Estimates suggest that the companies in the Fortune 500 still lose a combined $31.5 billion per year from employees failing to share knowledge effectively [219], demonstrating a need for increased collaboration. The trade-off between security and collaboration has been recognized and explored in works such as [136]. Attempts have been made to understand the user-base of such systems through semi-structured interviews with data analysts across several domains [139]. This work explored the broad categories of data analysts and their relationship both with information visualization technology as well as other technologists in their organization. Although collaboration was identified as important, a lack of tools to support it was reported to be a problem. Seldmair et al. [268] showed that confidentiality is a challenge that influences all phases (pre-design, during-design, post-design) of information visualization researchers work in a large company setting. Central to this challenge is the inability to freely collaborate and disseminate results due to confidentiality requirements. Collaboration in academic research suffers from similar tensions between secrecy and collaboration [57], particularly in fields where there is a high degree of competition [323].

Without effective collaboration tools that provide capability to protect sensitive data, collaboration may not happen at all, or much error prone manual effort may be required. Even if the collaboration is deemed important enough to share data, inefficient means are used to provide the data. Often projects must suffer significant delays while data is manually sanitized. This process may be error prone as it can be difficult for those sanitizing the data to understand fully what must be removed. Scrubbing a dataset prior to collaboration is not dynamic and time and effort is required to add or remove further data. When providing data in this manner, either too much data may be removed, causing delays or ineffective collaboration or too much data may be retained, exposing the data owner to unnecessary risk. Even if legal protections are in place, if too much information is shared, it is still ”in the wild” and the data owner must hope that the legal protections are sufficient to prevent further dissemination of the data, either intentional or inadvertent.

By providing tools that assist with navigating the tension between cooperation and competition, barriers to collaboration may be reduced, allowing the benefits of faster innovation cycles and knowledge sharing to be realized. Although existing computer security measures applied properly can effectively protect information at rest from attackers, there is less focus on how to provide a strong trusted computing base [38] while promoting collaboration across a variety of technologies to ensure effective shared knowledge discovery across domains and organizational silos. Scenarios such as this imply active dissemination of information across varied channels and across a wide range of devices for delivery to diverse audiences that have different levels of clearance.

Providing high-quality tools for collaboration is an important part of any solution. Without a fit-for-purpose tool that provides an acceptable collaboration experience relevant to users, there will not be a collaboration to secure since no one would use it. Immersive technologies such as virtual and augmented reality have shown the potential to become highly effective collaboration tools. However, as new technologies such as augmented reality (AR) and virtual reality (VR) are used in industrial applications, careful attention must be paid to the usability and security of these tools. For this reason it is important to assess how the technologies will be used, as well as what risks may exist as they are adopted, especially in combination with other tools.

With this analysis in hand it is possible to derive solutions that have the potential to be secure, usable and fit-for-purpose. Such a system would ideally be able to allow for effective collaboration and information dissemination while allowing collaborators to maintain greater control over their data. Ideally, collaborators would be able to maintain the principle of least privilege [264], where only the minimum amount of information is shared to achieve a collaboration goal. If technologies such as augmented and virtual reality can be applied to improve the collaboration experience when sharing information, perhaps they can also be applied to improve the protection of information in this context. Ideally, such a solution would allow all parties to work together on the same dataset, with protections in place and with careful integration of visual interactive computing technologies to allow users to share information in a dynamic yet secure manner that allows them to mediate their information as needed to achieve the collaboration goal.

A variety of scenarios have been considered, including co-located collaboration involving public displays and personal devices, virtual reality collaboration, augmented reality collaboration and mixed-reality collaboration scenarios where physical collaboration and virtual collaboration are occurring simultaneously. The mixed-reality collaboration scenario has the most interesting security concerns, as users must be aware of how information flows within and between at least two collaboration spaces. Based on the increased complexity of such scenarios, and on previous works that investigate collaboration in these environments, managing the flow of information in this situation is difficult for users. A proof of concept system is demonstrated in a mixed-reality scenario that combines simple access control and visual protection mechanisms in order to support collaborative scientific work over sensitive data. The access control and visual protection mechanisms allow users to protect their information by restricting what information is visible by other collaborators. This allows users to maintain control over their information and negotiate what is disclosed with other collaborators according to their needs and preferences. This allows control over the flow of information within the virtual space. The relevance and effectiveness of this approach to mediate the flow of information between collaborators is evaluated in two feedback sessions. Another way that the flow of information should be protected is by guarding against inadvertent information leakage across boundaries between collaboration spaces, such as between the physical space and the virtual space in a mixed-reality collaboration. In order to verify that this is a problem, a simple test to validate that users may easily be confused as to how information flows between collaboration spaces was implemented. Access control policy that considers the boundaries between spaces and the nature of both the boundary and the collaboration spaces could be used to prevent inadvertent information leakage in these situations although this was not implemented. Collaboration over data can be performed using this tool, while providing a means of protecting information and disclosing information only as required for the collaboration. Collaboration is crucial to rapid and effective work and can provide a great competitive advantage for organizations. Addressing one of the major barriers to collaboration, the sharing of sensitive data, through exploration of a prototype will help develop better methods of controlling the flow of information and will help organizations achieve their goals more quickly and effectively. This system can be used to validate and explore possible solutions, as well as create further discussion.

One of the primary uses for the Energi Simulation / Frank and Sarah Meyer Collaboration Centre is to support oil and gas reservoir modelling and simulation research. The techniques presented in this work are demonstrated in the context of reservoir engineering data. In reservoir engineering scenarios, parties with different levels of access will be engaging in collaboration over complex and varied data to make high-impact decisions. Typically, this data will be sensitive due to both the high cost of acquisition of data and often proprietary ways it may be interpreted and processed. For this reason it is a domain that benefits from high quality analysis and visualization tools that provide collaborative security mechanisms. However, the tool and techniques described in this work are not limited to any particular field and may be extended to many different fields where parties are collaborating over sensitive datasets or information. As an example, the two figures below show some example engineering collaboration scenarios involving a variety of technologies that could potentially involve sensitive information.

Figure 1.5: Immersive collaboration at Raytheon [248].

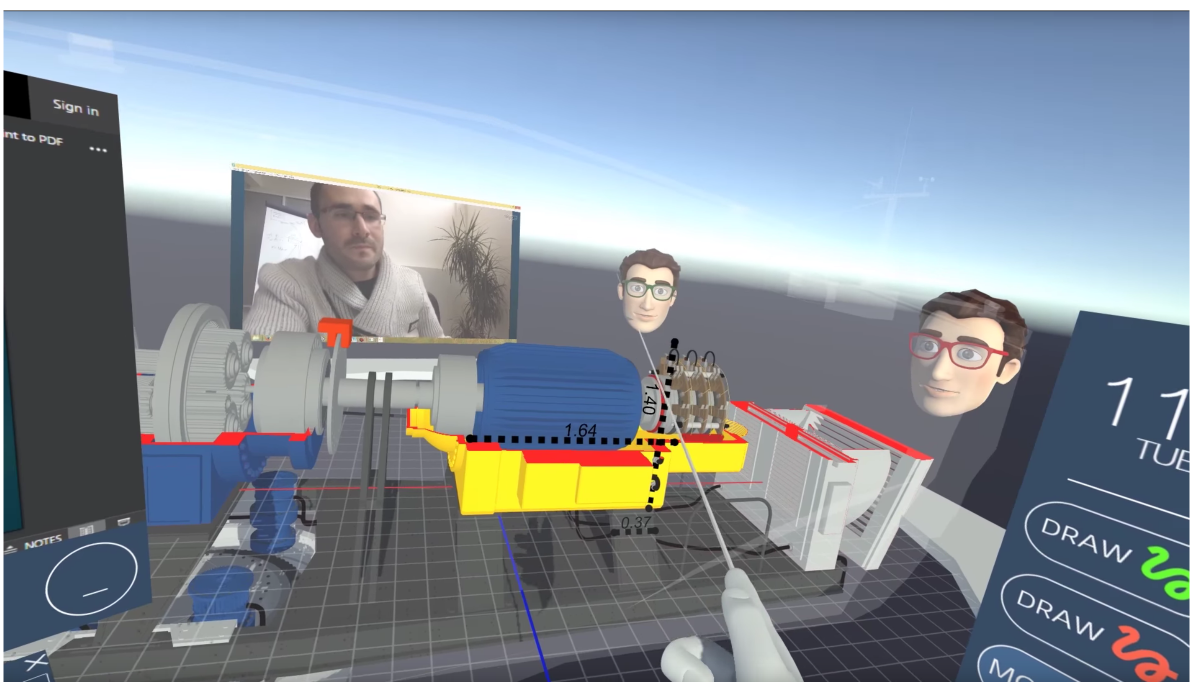

Figure 1.6: Improov3 – a virtual collaboration platform for professionals [212].

1.2 Research Questions

The objective of this thesis is to explore and answer the following research questions:

1. How can immersive technologies be used to collaborate over data?
2. What some are representative scenarios that can be used to understand the use of these technologies when collaborating?
3. How can the dissemination of information be controlled to provide protections that enable dynamic and secure sharing of information?
4. What access control polices may support the collaboration scenarios and appropriately regulate the flow of information in these situations?
5. What protection mechanisms can be used with these access control polices to enable dynamic yet secure sharing of information when collaborating over scientific data?

1.3 Contribution

In order to explore security concerns across the reality-virtuality continuum, it is necessary to have tools that could plausibly be used in a realistic setting involving sensitive data. For this reason, the first need is to develop an immersive tool that provides some potential value to oil and gas reservoir engineers. Then, collaboration capabilities must be added to the tool. Some potential scenarios across the reality-virtuality continuum in which the tool may be used must be considered, and the security concerns elucidated. Finally, the security mechanisms must be added and evaluated to determine if they are useful and realistic for use in a reservoir engineering setting. With this in mind, the contributions of this thesis are:

1. Development of a tool for collaborative, immersive reservoir visualization. This tool is described in Chapter 4.
2. Exploration of collaboration scenarios using a variety of technologies. Several important scenarios are explored in Chapter 5.

3. Discussion of architectural considerations for secure collaboration across the reality-virtuality continuum. Some security considerations are also explored in Chapter 5 and the implemented security mechanisms are described in Chapter 6.
4. Development of a prototype tool for collaborating over sensitive petroleum reservoir engineering data using a variety of technologies. This tool is described in Chapter 7.
5. Discussion and results of a feedback session involving reservoir engineering subject matter experts. The evaluation is described and results reported in Chapter 7.

1.4 Thesis Overview

The remainder of this work is organized as follows:

- The second chapter will provide the context and background of the problem. This involves discussion of the general context in which collaboration over scientific data occurs, the value of immersion for scientific visualization, immersive technologies, collaboration, reservoir engineering and an overview of some important security concepts.
- The third chapter provides an overview of existing work related to secure collaboration, particularly involving immersive technologies.
- The fourth chapter describes the immersive collaboration tool that has been developed for working with reservoir engineering data.
- The fifth chapter describes several collaboration scenarios and some of the security considerations associated with them.
- The sixth chapter describes the access control and visual protection mechanisms that were implemented in the secure collaboration prototype.
- The seventh chapter describes the feedback sessions for the prototype and the evaluation by subject matter experts.
- The eighth chapter provides directions for future work and the conclusion.

Chapter 2

Background

Effective collaboration is critical to project and organizational success in the modern world. Immersive technologies provide many benefits that can help develop effective collaboration tools. However security concerns often hinder collaboration when sensitive data or information is concerned. For this reason, it is important to find ways that these security concerns may be addressed, so that effective collaboration can occur even when sensitive data or information is present. Although this work is generalizable to many fields, the focus is on collaboration over scientific data, highlighted with a use case in petroleum reservoir engineering. Visualization of scientific data typically involves analysis of complex, three dimensional datasets. This kind of analysis can benefit a great deal from the use of immersive technologies. Further to this, many disciplines that require analysis of this type of data, such as petroleum engineering and medicine, require collaboration amongst various experts to successfully achieve desirable outcomes. These fields also commonly work with sensitive data. For this reason they have the most obvious need for immersive collaboration tools that allow for more effective analysis of this data while allowing collaborators control over the dissemination of information. In this chapter the context of visualization within scientific computing is briefly discussed. The tools and technologies that are used, including immersive technologies are explained. Some discussion of the application of these technologies to petroleum engineering is provided since this is the subject domain used in the example implementation of the immersive collaboration tool. Finally, a brief background related to the proposed security solutions is provided.

2.1 Scientific Computing

Scientific computing traditionally involves harnessing large computational resources to solve computationally intensive problems related to behaviours in scientifc fields such as physics or chemistry. Although scientific computing may suggest an non-industrial, academic context to some, scientific computing is pervasive in many industrial fields such as medicine and engineering. The explosion of data being processed and created requires big data techniques to be integrated [21]. High-end data analytics (HDA), or ”big data” and high performance computing (HPC) techniques are both essential elements of an integrated computing research-and-development agenda. Many fields that historically were not seen as computationally intensive such as the Social Sciences are incorporating big data techniques or high performance computing into their domains [182]. This is due to the large quantities of data increasingly available in these fields and the greater accessability of compute resources. Once data is collected, it must typically be processed in order to convert it into something that is usable to solve a problem. Processing may take a variety of forms such as formating and categorizing data, data mining, machine learning workflows or numerical calcuations such as those used for simulation. Historically, the dominant form of processing was to perform calculations on some single computational resource, such as a supercomputer. The rise of the compute cluster such as initiated by BEOWULF [291] caused parallelism and distributed techniques to become much more important. Today not all compute clusters are implemented using commodity hardware, but parallelism and distributed computing have become even more important in order to tackle the scale and complexity of most modern computational problems. For this reason modern computational apporaches are generally focused on breaking apart problems so that they may be solved in parallel [193]. Data processing may be performed as batch processing or stream processing. With batch processing, the processing occurs over a large static dataset and the result is returned when the processing is complete. Stream processing processes data as it comes into the system. Rather than determining how to apply operations to the whole dataset, stream processing techniques are focused on defining operations that will be appied to data as it enters the system. Apache Hadoop [15], implements MapReduce [68] and is still one of the top frameworks in use at the time of this writing for batch processing, even though it was one of the first ”big data” frameworks. Apache Spark [17] is becoming a more poplular processing engine for batch processing that also supports stream processing. Spark is becoming more popular than Hadoop as it supports additional features, supports in-memory processing and supports more flexible workflows than Hadoop. Tools such as Apache Storm [18], Apache Samza [16] are focused on stream processing. Apache Flink [14] is another stream processing system that can also handle batch processing. Currently many computing systems are processor centric, meaning the data moves to where it will be processed. However with ever-increasing distribution and scale of data to be processed, this movement is quite problematic. A solution to this is data-centric computing, where workflows are data-oriented, and processing is moved to where the data naturally resides [47].

As data is collected and processed, more data and metadata is generated. Metadata may include access and modification history, version history and data provenance information. All of this data must be managed to organize it both in terms of content, but also to organize it according to properties such as project or owner. For this reason, data management is becoming very important. While a variety of solutions have been explored [110] [96], proper data management has many challenges, especially in collaboration scenarios where different parties are simultaneously interacting with and creating content [203]. Another challenge is that the scale of problems being explored in many domains as been so great, that high performance computing techniques may need to be applied even to mange the data [106]. Data management can often be domain specific. For example a system for managing data for computational fluid dynamics simulations specifically has been proposed [269].

Data may be structured or unstructured. Structured data has a predetermined structure such as that coming from forms or databases. Examples of structured data sources include systems where the inputs are controlled, such as Enterprise Resource Planning (ERP) or Customer Relationship Management (CRM) systems. Unstructured data is generally seen as everything else, that is data

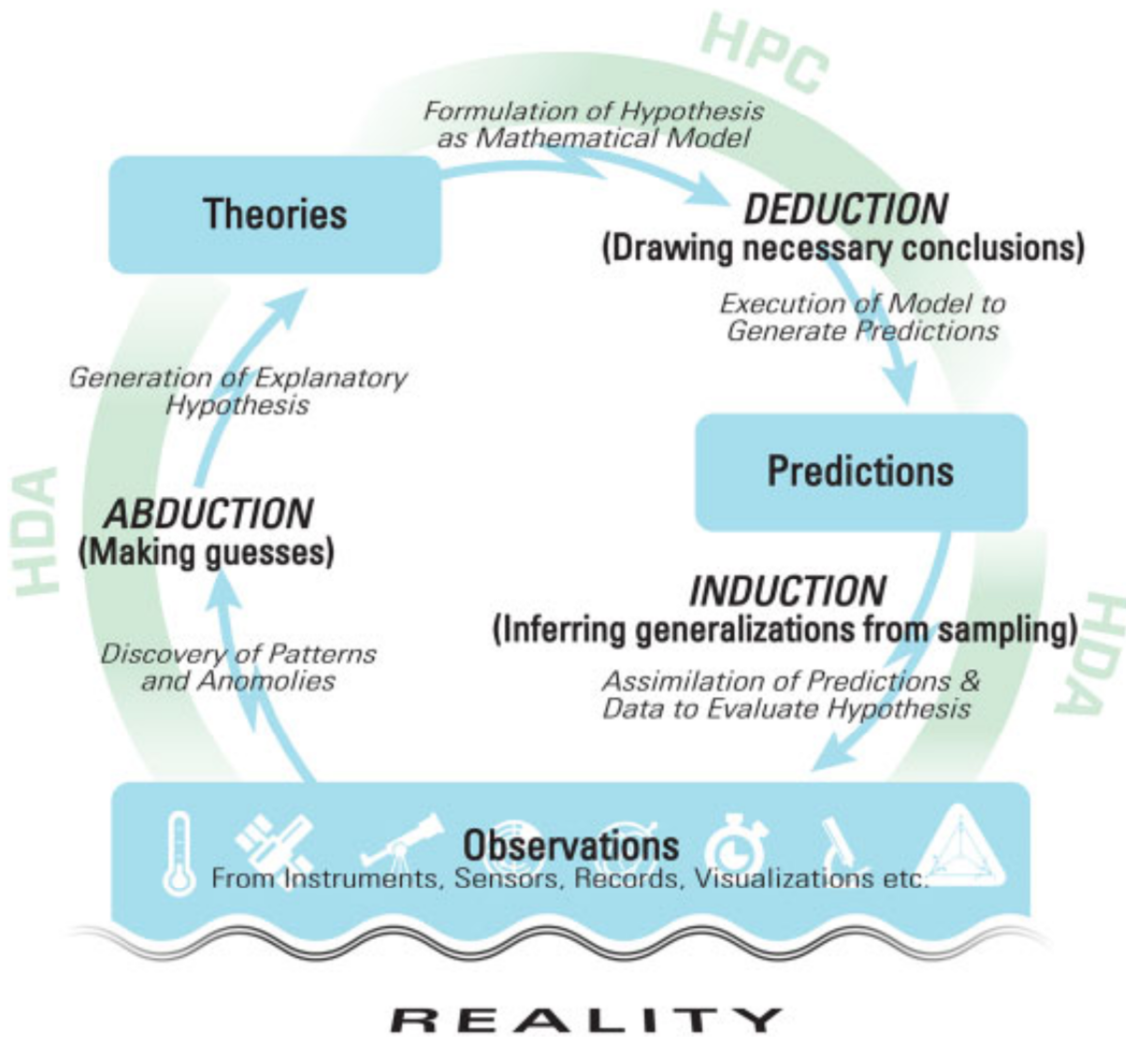

Figure 2.1: The inference cycle integrating both high-end data analytics (HDA) and high performance computing (HPC) for the process of scientific inquiry [21].

that is not well organized and may not come in a clearly defined format. This can include for example a wide variety of data such as files, scientific data, image data or sensor data. Even if a particular piece of data has a structured format, such as image files or documents, the content contained within that format is unstructured.

A Workflow Management System (WfMS) is a system that is critical to complex data processing environments and defines, creates, and manages the execution of workflows [63] [172]. A WfMS is able to interpret the workflow process definition typically in the context of business applications. A SWfMS is a WfMS that handles and manages scientific workflow execution. Scientific workflow management systems (SWFMSs) have been developed to help domain scientists synergistically integrate distributed computations, datasets, and analysis tools to enable and accelerate scientific discoveries. As the variety, velocity and volume of data increases and computational tasks become more complex, management of data is of critical importance to remain organized and secure. This has lead to increased use of Scientific Workflow Management Systems (SWfMSs) [194]. In particular, data-inensive scientific workflows have special considerations to support the large data sets found in modern scientific computing environments [194]. Many SWfMSs are composed of five layers. A common separation is the presentation layer, user services layer, workload execution plan (WEP) generation layer, WEP execution layer and infrastructure layer. These five layers enable SWfMSs users to design, execute and analyze data-intensive scientific workflows throughout the data lifecyle. The aim of scientific workflow systems is to support computational science and accelerate scientific discovery in various ways such as by providing process automation, scalable execution, abstraction, and provenance support (ASAP for short) [63]. In many situations, there are several processes required to achieve a scientific objective. These processes may be simple linear sequences of tasks, or complex graphs of dependencies. Automation of these processes is important so that these scientific objectives may be achieved effectively. Scalable execution refers to the ability to handle compute-intensive and big data loads by supporting distributed and parallel workflows. This includes support for cloud and grid compute resources. There are many considerations when developing SWFMSs that support collaboration [197]. Developing an effective collaborative system requires understanding the sophisticated interaction and hierarchical composition of various dataflows and collaboration patterns to model complex and large-scale scientific workflows. Much thought is also required to capture, manage, and utilize large amounts of distributed, heterogeneous, multi-level, and collaborative provenance data for the reproducibility of scientific results produced from collaborative scientific workflows.

Although provenance has several different meanings in Computer Science [201], in the scientific computing context it refers to the mechanisms that track the use and creation of information over time. This ”data lineage” facilitates reproducible science [63]. Provenance is also very important when analyzing and visualizing data as evidenced by tools such as VisTrails [48], which manages the data and metadata of visualization products. VisTrails allows for the ability to explore visualizations by returning to previous versions of a visualization pipeline. Users may also apply a dataflow instance to different data, explore the parameter space of the dataflow, query the visualization history and comparatively visualize different results. This information is very valuable to determine how insights were generated, and to avoid duplication of work.

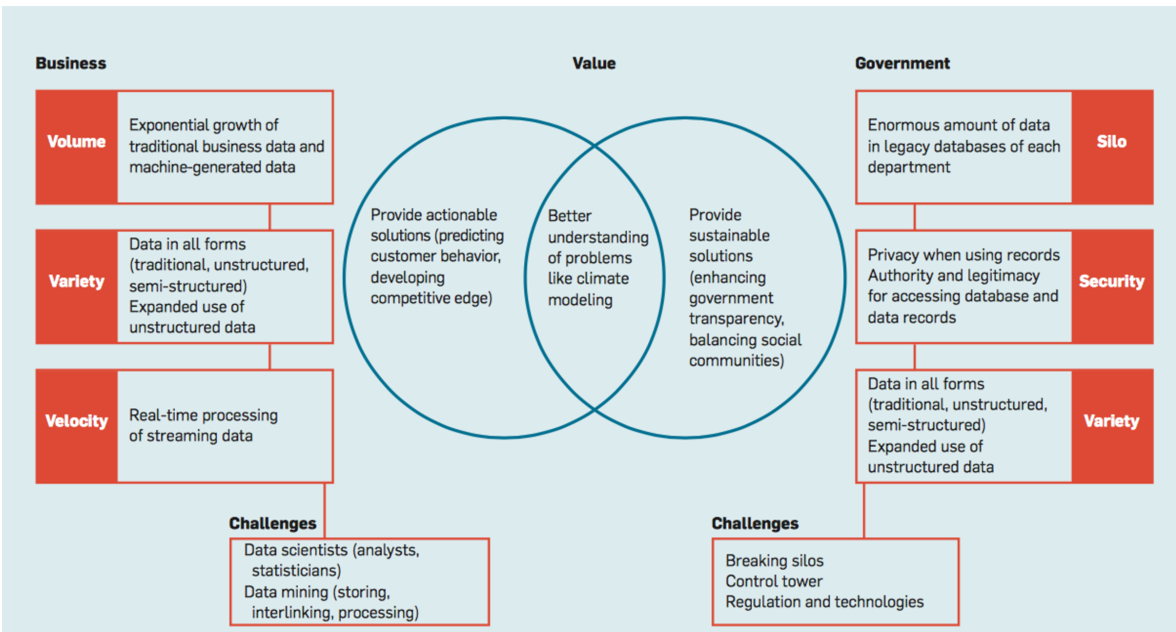

Figure 2.2: Getting value out of big data may have different meanings and challenges across sectors but always requires tools that can help solve relevant problems [151].

Traditionally scientific discovery consisted of developing theories and designing physical experiments to validate these theories. Now, however computing has become the ”third pillar” of science, enabling researchers to use mathematical models to predict complex behavior in senarios such as where the problem is too large or complex to understand through physical experiements, the experiments would be too dangerous to perform safely or the problem is not cost effective to solve by other means. As a result, computational science is now widely used in many diciplines [242]. As businesses wrestle with more complex problems and an expectation to be data-driven, scientific computing is no longer solely within the purview of academic research. Commercial research and even commercial operations are relying more and more on scientific computing to perform tasks such as simulation and data analytics. The influx and collection of data has lead to the rise of ”big data” and the scientific community, businesses and governments are all focused on leveraging scientific computing techniques to better understand complex problems and create value [151]. With the rise of big data there are many challenges that must be addressed holistically, including privacy, visualization and collaboration [132].

Data life cycle stages	Activities
Data collection	Recording provenance, data acquisition
Data preprocessing	Data movement (ingestion), cleaning, quality control, filtering, culling, metadata extraction, recording provenance
Data processing	Data movement (moving across different levels of storage hierarchy), computation, analysis, data mining, visualization (for selective processing and refinement), recording provenance
Data post-processing	Data movement (newly generated data from processing stage), formatting and report generation, visualization (viewing of results), recording provenance
Data sharing	Data movement (dissemination to end-users), publishing on portals, data access including cloud-based sharing, recording provenance
Data storage and archival	Data movement (across primary, secondary, and tertiary storage media), database management, aggregation for archival, recording provenance
Data preservation	Checking integrity, performing migration from one storage media to other as the hardware or software technologies become obsolete, recording provenance
Data destruction	Shredding or permanent wiping of data

Figure 2.3: Various stages of the data life cycle [106].

The data lifecycle in the scientific computing context consists of several iterations, and while there are numerous variations of the theme, the stages described by Gomez-Iglesias [106] are representative. Throughout the lifecycle there are many tasks that must be accomplished. Within the context of collaboration, the most important tasks relate to the dissemination and retrieval of data, information, or knowledge. The difference between data, information and knowledge is not well defined [344]. As described by Anthony Liew in [190], data is is the capture, storage, structure, compilation, retrieval, and analysis of records such as media or scienfic measurements. Activities related to data include reconstructing recent historical events for decision making or problem solving. Data is entirely empirical. Information is also likely empirical but probably represents a higher degree of processing or analysis and thus higher value. One way to view knowledge could be the insights gleaned from information. Knowledge may be empirical or not but would typically fit within a cognitive framework that makes it possible for humans to use information. The integration of information into this cognitive framework generates insights that may be recorded or used directly to generate more data or information. The conversion of information into insight and knowledge may lead to responses that are measurable and therefore empirical. An attempt to form a knowledge generating framework for visual analytics is described in [259]. This provides a more structured approach to relating the formation of knowledge within the data life cycle. The focus in this research is not to determine a universal data-information-knowledge model, but rather to emphasize that effective collaboration must safeguard users preference for sharing any one of these categories in their version of a data-information-knowledge model.

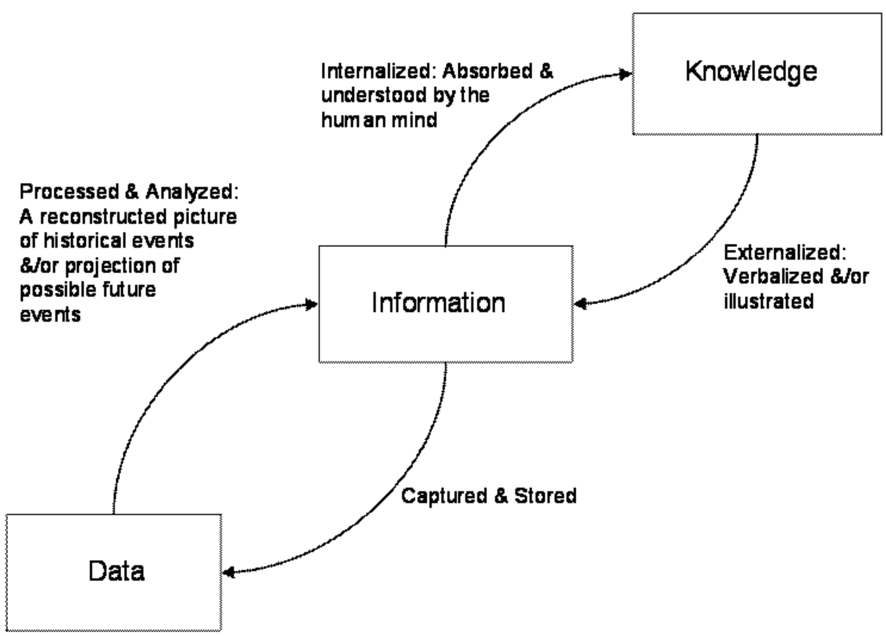

Figure 2.4: Relationships amongst knowledge, information, and data [190].

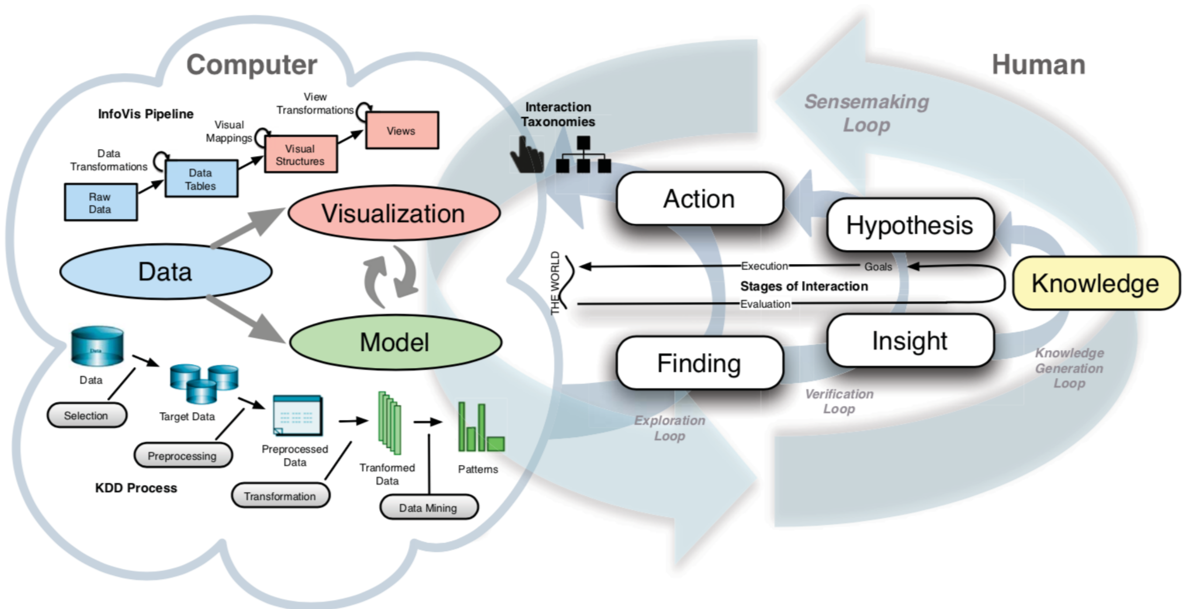

Figure 2.5: Relating the process model for knowledge generation in visual analytics to other models and theories [259].

The scenarios being considered for analysis are increasingly vast and more detailed, resulting in larger volumes, varieties and velocities of data. Approaches such as data mining and artificial intelligence provide even greater potential to solve challenging problems, but can also require more analysis to verify and understand their results [138] [298]. An increasingly wide variety of visual interactive computing technologies are available to visualize and interact with data, creating opportunity to provide more effective tools and greater analysis capabilities. Dynamic and complex information sharing scenarios are becoming more common as is the migration of data across organizations and geographical boundaries. As scientific computing tools and techniques become more popular, both how to share information, data or knowledge, and how to provide security assurances while doing so are major challenges [72]. It may be desirable to share only raw data, rather than information. When sharing and managing data, it may be possible to provide information, in the form of processed data or visualizations, while restricting parts of the data supporting this information. Knowledge and insights gained through ingestion of information may be the most valuable of all, which could result in an increased incentive to share but also possibly an increased incentive to hide such insights.

2.2 Visualization

Visualization of data is very important so patterns that may not be easily understood from purely statistical data analysis can be elucidated. Many of the data visualization tools we see today have their roots in techniques developed before the 20th century. [99]. Despite this, in 1973 Francis Anscombe was compelled to develop an example to demonstrate the value of visualizing data using graphs as part of the analysis process. Commonly referred to as Anscombeś Quartet [13], this example shows the value of visualizing data by graphing four carefully crafted datasets that have very similar summary statistics so they are difficult to tell apart using statistical analysis. When graphed, however, the impact of outliers and the difference between the datasets are readily apparent as their graphs vary wildly. This example was required since in 1973 graphs were considered rough, whereas numerical calculation were consider exact, so visual analysis was not popular. The genesis of visualization in scientific computing as a mainstream topic has been associated with the 1987 report ”Visualization in Scientific Computing (VISC): Definition, Domain and Recommendations” [206]. Ever since that time, there has been an increasing awareness of the importance of visual analysis within a scientific computing context.

Much like processing, visualization has undergone many architectural changes as computing technology has evolved. The rise of personal devices, such as tablets and smartphones, and the ubiquity of computing devices in general has driven interest in a variety of visualization approaches [90]. Client rendering, such as on mobile devices [225] or using WebGL [150], is useful if connection to a network is not reliable or a connection to a central service to perform tasks is not desired. However, it is dependent on sufficient capacity and hardware on the client, and rapidly breaks down if large amounts of data must be transferred to the client. Remote rendering [276], using tools such as Paraview Catalyst [22], allow the graphics processing load to be shifted to the server rather than the client. These techniques, however, can lead to increased bandwidth use and a lack of interactivity resulting in a reduced user experience.

Hybrid rendering has been used as compromise between client side rendering and server side rendering, where some processing is done on the client and some on the server. An example is [209] which describes hybrid visualization tools to improve visualization performance in 3D virtual reality systems such as CAVEs and Powerwalls, as well as augmented reality. Visualization workload may even be shifted between client and server dynamically as needed due to performance variability in the system [299]. Hybrid rendering can reduce data movement by performing some processing on the server, while allowing some data to be processed on the client. This can make an application very responsive, supporting high frame rates with large data sets even with highly interactive applications and when network quality may not be ideal. The benefits of hybrid rendering are particularly important for immersive visualization [292] where latency issues can cause problems such as increasing the risk of VR sickness.

2.3 Immersion

Immersion refers to the objective level of sensory fidelity a VR system provides. Immersive systems can contribute to a sense of presence [208], which is the psychological response to the increased sensory fidelity. Presence is a measure of how much the user feels that they are actually in a virtual world. Presence typically requires immersion; however, not all immersive systems have a high degree of presence. Presence is of critical importance to many areas such as architecture, educational and entertainment. Presence on its own has less direct benefits to scientific visualization, however, a system that provides a high degree presence may allow a user to focus on the data and problem at hand without distraction. The technical factors that contribute to immersion can be separated into different components that can be delivered independently of the other components. Although the effects of these components can be studied separately, they typically combine to provide a level of immersion when working together that is greater than the contribution of each individually. There are various factors that contribute to immersion. According to Dr. Doug Bowman these factors include [36]:

- Field of view (FOV) – the size of the visual field (in degrees of visual angle) that can be viewed instantaneously
- Field of regard (FOR) – the total size of the visual field (in degrees of visual angle) surrounding the user
- Display size
- Display resolution
- Stereoscopy – different images are displayed to each eye, providing a depth cue
- Head-based rendering – images are displayed based on head position and orientation
- Realism of lighting
- Frame rate
- Refresh rate

Currently VR and AR are undergoing a renaissance, with a large amount of effort and investment focused on improving the hardware and software underlying these technologies. This will go a long way to improving many of the factors that contribute to immersion.

Several benefits can be realized through the use of immersive environments for collaborating over data. These include:

1. Improved spatial perception
2. Easy interactions
3. Large working space
4. Highly effective collaboration

Stereoscopic 3D combined with head tracking in particular provides improved depth cues and spatial understanding. This allows for faster understanding of data and scenarios, and helps ensure that key information is not missed [169] [168] [243] [23]. This can also help significantly when working together with collaborators, since all participants in the collaboration have improved spatial understanding, improving the accuracy of communication and therefore the effectiveness of the collaboration [79].

Easy interactions allow the user to focus on the application and not user interface. Providing a variety of ways of interacting allows far more possibilities than traditional interfaces such as keyboards and mice [179]. Users may use voice, gestures, body movements, advanced controllers or any combination to perform actions in an immersive environment. This supports the goals of design principles such as Reality Based Interaction [131]. Moving beyond the mouse and keyboard can reduce cognitive load and promote fluid interactions supporting optimal flow states, and generally improve outcomes when analyzing complex datasets [85].

A large working space reduces information clutter and allows users to spread out their workflow over a spatial region [204]. This allows users to stay organized and understand how information is linked since visual analytics tools can be viewed with the context of data such as 3D simulation models directly. This allows the user to understand relationships between quantitative data and what is occurring in a scenario. When collaborating this is even more effective, since users can work together in this large virtual space in a manner that reflects how they are used to working together in person.

These benefits have a synergistic effect when combined. The easy and intuitive interactions and the large working space combine to let users work together effectively, while leveraging the increased spatial perception to improve understanding and communication. This allows users to build common understanding and rapidly assess information, especially when complex, three dimensional datasets or scenarios are involved. These benefits apply both scientific visualization [169] [168] [243] and information visualization [39] [215] [321] [45] [244] [103]. Many 2D information visualization methods have been extended to immersive environments [43]. The use of immersion has been shown to have a variety of benefits in a many domains including mining [308], manufacturing, and product design [29]. Immersion has long been seen as a useful technology for collaborating [221], and a host of new works are proving this value.

2.4 Immersive Devices

There are a variety of immersive technologies that fall into three broad categories. The first is entry level portable devices such as smartphone-based VR and AR. The second is mid-tier devices such as the Oculus Rift [230] and HTC Vive [122]. The third category is large, industrial systems that can be outfitted with a large amount of computational power, advanced tracking technologies, low latency and high bandwidth connections to compute resources and high resolution displays, ideally to support group work on large or complex datasets.

Figure 2.6: Operating a virtual Canadarm using an Oculus Rift CV1 with Ultrahaptics for NSERC Science Odyssey.

2.4.1 Large Scale Visualization Facilities

Ideally, applications should work seamlessly on a variety of platforms, moving between head mounted displays (HMDs) and large scale visualization facilities [218]. Large scale visualization environments based on the original CAVE have provided a large amount of value for many groups [31] [163]. In both academic and industrial environments, large-scale permanent immersive facilities are typically combined with a variety of other visualization resources such as high-resolution display walls, portable visualization hardware and consumer grade devices. Even designs based on the original CAVE have provided an effective way for groups of co-located individuals to collaborate over data and understand scenarios while maintaining proprioception and interpersonal connection. For larger groups such a facility can be easier to use than many head mounted displays, since many individuals may be brought into a scenario together without the time consuming process of fitting all the group members with head mounted displays and then training them on the devices and the software. Users also find the comfort of lightweight stereoscopic glasses and the interpersonal connection that is maintained in such environments to be desirable compared to virtual reality (VR) head mounted displays for co-located collaboration. The augmented reality (AR) head mounted displays that are currently available lack the visual features and the computational capacity to be compelling for data-intensive scientific work. Although this technology will become much better over time, it will be a long time before the visual characteristics and computational power of commodity devices can compare to a dedicated, large scale visualization infrastructure. Also, it will likely be a long time before headsets capable of industrial work are as comfortable over time as lightweight stereo glasses. Users have also reported that for applications such as working with reservoir data, the additional visual clutter introduced by viewing the physical environment while working in augmented reality is not needed and may actually be a distraction. Extremely high resolution display panels and projectors utilizing laser-based technology are far superior to previous technologies, providing a very high degree of visual fidelity in large-scale visualization environments, while requiring far less long term maintenance effort.

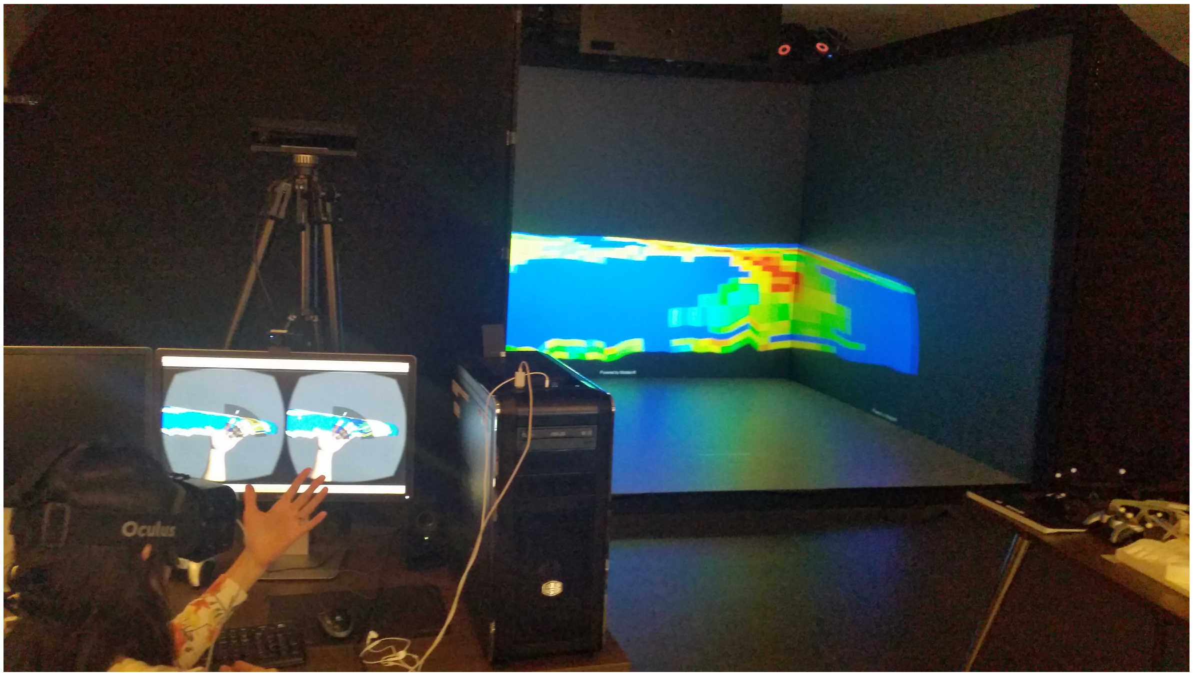

Figure 2.7: An application using a HMD with hand tracking, and the CAVE.

In additional to the original four sided CAVE, CAVEs may come with as many as six sides, vary greatly in size and tracking technology, and have been outfitted with a variety of movement devices, including spheres for walking [178] [159]. There are also many alternatives to the original CAVE design [69]. Some examples include CAVE2 [92], the Cyber-CANOE [143], StarCAVE [70], the AlloSphere [10] [162], the YURT [41] and the Reality Deck [236]. Domes also can be used to provide immersive experiences [174] and are increasingly shifting from simple large scale theatres to interactive visualization spaces [175] for science [166] or education [333]. Low cost and portable immersive systems have also been developed such as IQ-stations, which are mobile one wall inexpensive immersive displays [275] [274]. A variety of other approches to low cost, portable immersive sytems have also been proposed [34] [293] [293] [12] [127] [107] [140].

The original CAVE design does not support multiple correct stereoscopic view perspectives [240] [311]. Although this can be mitigated through software techniques [88] [286], typically only one person can be motion tracked at one time with the 3D viewpoint attached. When that person moves, others see a distorted view of 3D images unless they are standing very close to the tracked person to see the same viewpoint perspective. Newer systems such as the CAVE2 make use of Omnistereo [279] to support group collaboration with correct perspectives. Omnistereo is known by several other names including "Panoptic Stereo", "Panoptic 3D", and "Omnidirectional Stereo". Omnistereo rendering for each screen segment uses the fixed or tracked head position, but determines eye locations and a viewing direction normal to each screen segment. In this case all viewers still share the perspective of the tracked head position, although they are also free to move around looking in any direction and still have a reasonably comfortable stereo viewing experience. The stereo image pair for each wall segment is rendered as if the tracked viewer were looking directly at the plane of each screen segment. There is no chance of a non-tracked viewer not seeing stereo or seeing a reversed stereo image. Omnistereo imaging creates a panoramic-scale representation of an entire 3D scene by pre-generating multiple viewpoints. All possible viewpoints are created before display. Even if one person is controlling the camera, the entire scene can move with correct perspective for all viewpoints. This enables large groups to share in an immersive tracked experience because images are not distorted to one viewpoint. The scene creation has to be taken into account in display design. Omnistereo will only present correctly when adjoining screens are at angles of 120 degrees or more.

The traditional cube shaped CAVE design can primarily be used only as a large scale VR environment. Many newer visualization spaces, including the Barco MoVE [25] and even more recently the CAVE2, are designed to be more versitile by suporting a variety of different visualization workflows including combining 2D, 3D, temporal, and multivariate datasets [249]. These workflows often require supporting software to make optimal use of the hardware [91].

Other visualization facilites may use projectors that directly support multiple correct stereoscopic views. For example Digital Projection [75] makes a MultiView projector based on the INSIGHT Dual Laser 4K projector that is based on research at Bauhaus University Weimar [101]. Normally, a projector operates at 120 Hz for high quality Active 3D stereoscopic viewing. The MultiView projector operates at 360 Hz providing three 120 Hz viewing times. Two projectors may be linked to provide six 120 Hz viewing times. If a 4th person viewed an image in a 3-viewer MultiView system using additional MultiView glasses, their eyewear would share the eyepoint (and sync pulse) of one of the three viewers in the system. This approach has provided excellent results [164] [100]. Other approaches have been developed using multiple projectors to provide a multi-user stereoscopic environment [113].

The ability to directly connect the visualization infrastructure via a fast, low latency interconnect to HPC or HDA compute resources is an advantage of this centralized infrastructure. The graphics pipeline workload may be shifted to a remote compute resource where data is stored, and computation is performed [193]. This allows distributed and remote visualzation techniques [4] [3] that are scalable to very large data sets without transmitting data back and forth to the client. However remote visualization has challenges such as latency, that can hinder the user experience in interactive applications [276]. A low-latency dedicated network connection between the computational resource and the visualization infrastructure can mitigate the limitations of remote rendering, and allow for fewer interaction design compromises. The integration of hybrid techniques that leverage the computational capacities on the client in these systems provides even more capabilities. A large amount of computational power can be integrated into a large scale visualization environment that can be leveraged to provide high-frame rates and fluid interaction with large datasets. This provdes more flexibility regarding the architecture which can improve the ability to visualize and interact with large models or data sets by leveraging the greater client graphics processing capabilites to enhance hybrid rendering schemes [87] [170]. The computational power on the client may also be leveraged for the processing of data [93]. Centralized visualization infrastructure with a large amount of graphics and data processing capability can provide an ideal tool for immersive analytics workflows [204] [285] especially in modern ”big data” scenarios. These visualization facilities are highly interactive and collaborative environments that support scientific visualization [231], product design, manufacturing [29], and education [303].

These large scale immersive visualization facilities may also be linked together with other visualization centres for greater collaborative capabilities. For instance, the University of Hawaii at Manoa is linking their visualzation resources such as the CyberCANOE across the Hawaiian Islands [143]. Other examples where visualization resources are linked include [241] and [97]. These visualization environments may also be linked with commodity immersive devices and non-immersive devices.

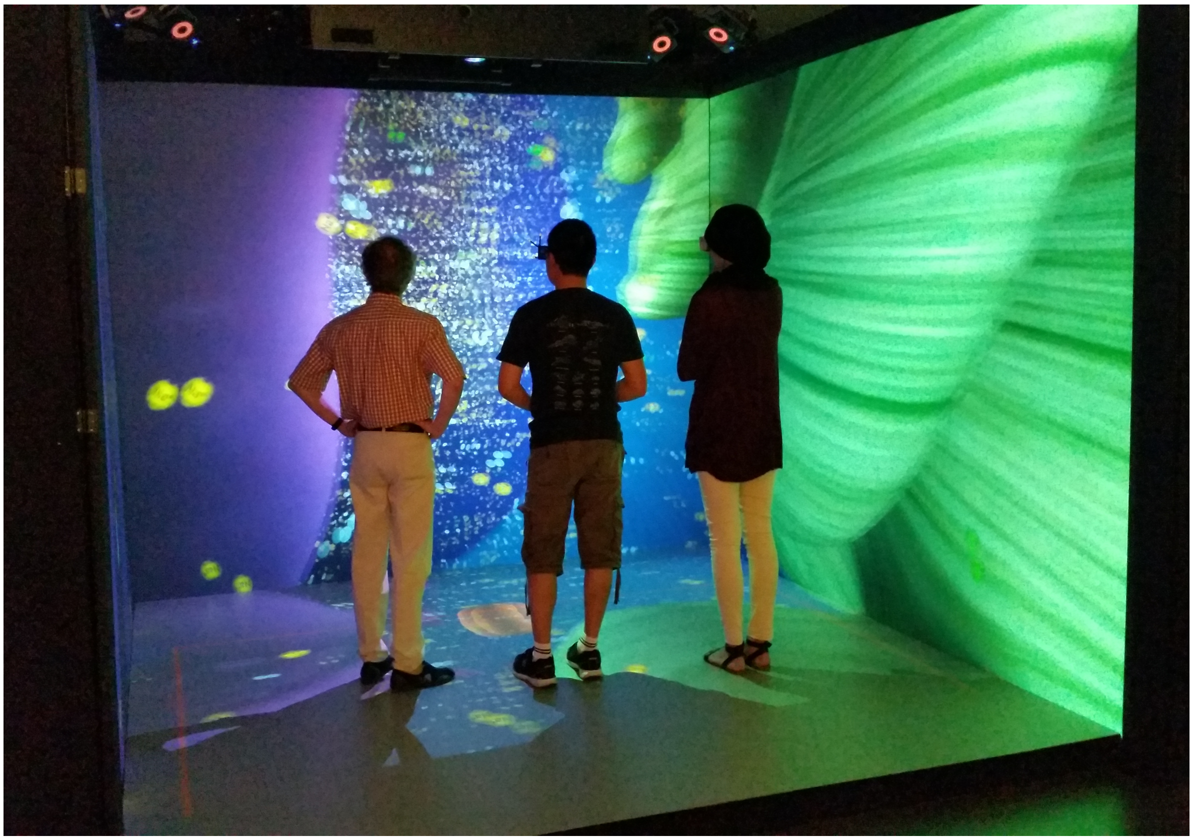

Figure 2.8: Exploration of an eukaryotic cell model in a CAVE [337] [338].

2.5 Collaboration

Within industrial organizational literature, there is a great deal of interest in both internal and external collaboration. Especially in industries where innovation is critical, it is often important for organizations to work closely with other organizations in an integrated, collaborative manner [66]. The formation of strategic alliances with other organizations is also very important [309]. Collaborative analysis of large datasets has shown great benefit for organizations [44], but only if certain conditions are met. There are many factors related to team dynamics that relate to the effectiveness of this teamwork. Careful design of tools can also help promote positive behaviors that support effective team dynamics. The rise of collaborative VR applications for science [129] or for social collaboration [320] [296] will lead to many security and privacy challenges in these environments. Works such as [234] have noted the possibility of using virtual worlds for collaboration, however they investigated public spaces such as Second Life, which are not suitable due to security concerns. Citi Holographic Workstation for Financial Trading [1] makes use of ad hoc mixed reality spaces for collaboration and discussion. This allows the trader to work with team members, colleagues, and clients in a way that is both personal and immediate. Although there is a willingness on the part of organizations to use immersive technologies, they will unlock the potential of these technologies only if they are carefully designed to facilitate effective collaboration.

The rise of innovation ecosystems, in which firms depend on one another to collectively provide and create value for consumer in a tight-knit network of integrated organizations, demands effective collaboration between organizations [65]. Partnerships between separate organizations to share resources collaboratively toward mutually beneficial goals is an important strategy. Among many desirable outcomes, alliances can reduce costs, provide access to new technology, and improve research and development endeavours. However, without the proper tools, this can be difficult for firms to manage. Collaborative arrangements come with risks and many challenges. To support these ways of working together, it is important to find ways to mitigate these risks, including supporting a high degree of control over the dissemination of information.

2.6 Application Domain: Reservoir Engineering

An industrial example of scientific computing is reservoir engineering. This is a highly technical field that relies heavily on mathematical modelling to represent the physical behaviors that underlie petroleum recovery techniques [54]. This typically involves understanding how fluids such as oil, gas and water propagate through porous media such as rock. There are many other physical behaviors that must be considered such as thermal physics, geomechanics, and even electromagnetics.

Oil and gas exploration, development and production use a large volume of extremely varied data that presents many visualization and analysis challenges. For instance, reservoir engineers must determine the optimal method of extracting hydrocarbons from the subsurface. Since the subsurface cannot be directly observed, several data sources are used to build a statistical model of the subsurface. The reservoir engineer must consider layers of porous media such as rock with different properties within the context of this model. These layers must have particular morphological features and properties that allow hydrocarbons to be trapped in place [105]. A key problem faced by reservoir engineers is to predict where fluids are located based on the geological property values and structure of the rock, and to predict how these fluids will flow through the media under different extraction scenarios. Therefore, they must both visualize the structure and also have a clear understanding of the properties and the predicted fluid flow behaviors within the model. Adding to the complexity, the model is based on uncertain and incomplete data, as well as interpretations of that data by subject matter experts [332]. For this reason it is extremely important to have tools that can clearly represent as much information as possible, and support collaboration between a variety of subject matter experts [82]. Most of the information that must be considered, such as a potential hydrocarbon trap, is contained within the volume of the subsurface model. However, it is highly context dependent, since the surrounding structure and properties will change the extraction plan. For this reason, it is important to have effective methods of visualizing the interior of the 3D volume, while maintaining important contextual information [67]. Volume data, such as used to visualize a subsurface model, consists of a 3D dataset discretized using a 3D grid. The 3D grid can take a variety of forms, each with their own unique challenges for visualization and analysis [289]. In a reservoir model, the morphology of specific features and general structure of the model are very important. This is represented by the position of the property values in the 3D grid. Each of these locations on the grid may contain many data values representing, for example, properties of the media that is visualized, such as the porosity or permeability of the rock, or the fluid content within the volume. Features such as wells and faults must be visualized, and the additional complexities introduced by fracture networks [7] or unconventional extraction methods [89] must also be visualized and analysed. Information must also provide appropriate access controls and protection mechanisms to safeguard information, while providing an effective collaboration experience.

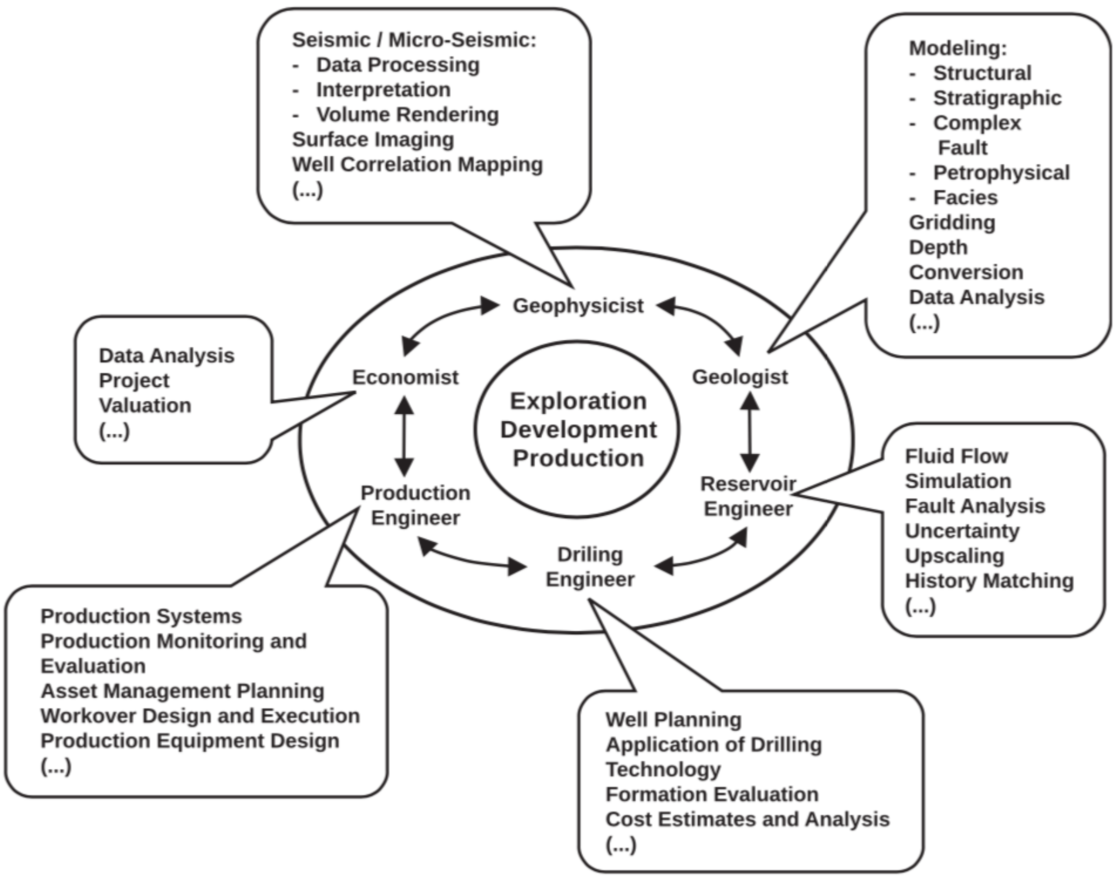

Figure 2.9: Collaboration is required across disciplines in oil and gas exploration throughout the exploration, development and production cycle [288].

Providing software and hardware tools that help users work with this data in an effective manner is very important. However, developing these tools is very challenging in a highly technical field working with these complex datasets. The use of visual interactive computing technologies is an effective and proven method to help with these complexities [287]. One particularly promising visual interactive computing technology that has been applied to scientific visualization challenges in general and reservoir engineering in particular is virtual reality.

When dealing with 3D volume data, especially when a large degree of spatial context is needed to perform analysis tasks involving spatial judgement or there are complex structures, immersion, a key component of virtual reality, has been shown to provide advantages [243]. These advantages include increased field of view, increased field of regard and increased perception of spatial relationships [36]. These perceptual advantages have been shown to improve tasks relevant to reservoir engineering for the analysis of volume data [169] and isosurface visualization of volume datasets [168]. The benefits of immersion extend beyond purely perceptual. The potential for intuitive and natural interactions is greater in immersive environments, and there is an increased working space in which to interact with data [37] [163]. Virtual reality provides the opportunity for collaborative tools that allow diverse teams to work together in a highly interactive and effective manner [79] [223]. Virtual reality is also an engaging and interactive medium for working with reservoir data, making it ideal for training and communication of complex ideas found in reservoir engineering. When the perceptual benefits of immersion are coupled with the high degree of interaction and collaboration and a large working space, we have tools that can improve the efficiencies of many workflows. For example, Halliburton has reported a reduction of certain tasks from 80 days to 8 hours using collaborative virtual reality tools [71].

Compared with the current situation, prior generations of virtual reality hardware consisted of far less capable hardware, vastly reduced graphics capabilities, and a very immature understanding of VR user experience design and 3D user interface design. This translated into expensive, difficult to use hardware, poor user experiences, frustrating interfaces, simulation sickness and a relative inability to design experiences to provide a high-value visual analytics experience that directly supports the user workflow. Despite these limitations, initial explorations of the technology showed many benefits relevant to the exploration of scientific data in general [316] and reservoir engineering in particular [213] [192] [189]. For instance, virtual reality has shown benefits for well path planning [111] and visualizing the internal micro-structure of rocks [144]. These early attempts at immersive applications were regarded as promising; however, several factors were identified by Kinsland and Borst that prevented immersion from fulfilling its promise [152]. Most of these factors were related to the lack of easy to use and accessible hardware as well as a lack of maturity regarding 3D user interfaces and immersive design principles. In the 1980s, 3D graphics were beginning to be used for reservoir simulation. However 3D graphics were not considered essential as it was thought engineers could do their work with 2D graphs [325]. Only in the 1990's was 3D graphics in reservoir simulation considered valuable [315]. It is possible that the previous lack of adoption of immersive technology is a natural growing pain as technology matures and industries eventually learn how to apply it to their business. Several reservoir engineering tools have been developed for analysing reservoir data in an effort to utilize modern hardware and design principles, while also attempting to mitigate the factors that were reported to hinder adoption in previous immersive tools for reservoir engineering. Tools such as [245] and [51] have received very positive feedback and have caused the industry to ask for further development of these tools so that they can be used for reservoir engineering work. This positive feedback is encouraging and suggests that VR may someday become integral to the oil and gas Industry in general and reservoir simulation in particular.

The importance of innovation and technology in sustaining the petroleum and petrochemical industry is well understood, and virtual reality is playing an increasingly important role in the industry [340] [119]. Modern virtual reality has already provided benefit to many other professional scientific fields such as medicine [76], physics [220], biology [81], and geosciences [31]. This technology has the capability to transform and drive efficiencies in a variety of industries, and the development of tools in reservoir engineering provides concepts and techniques that may be applied to all industries.

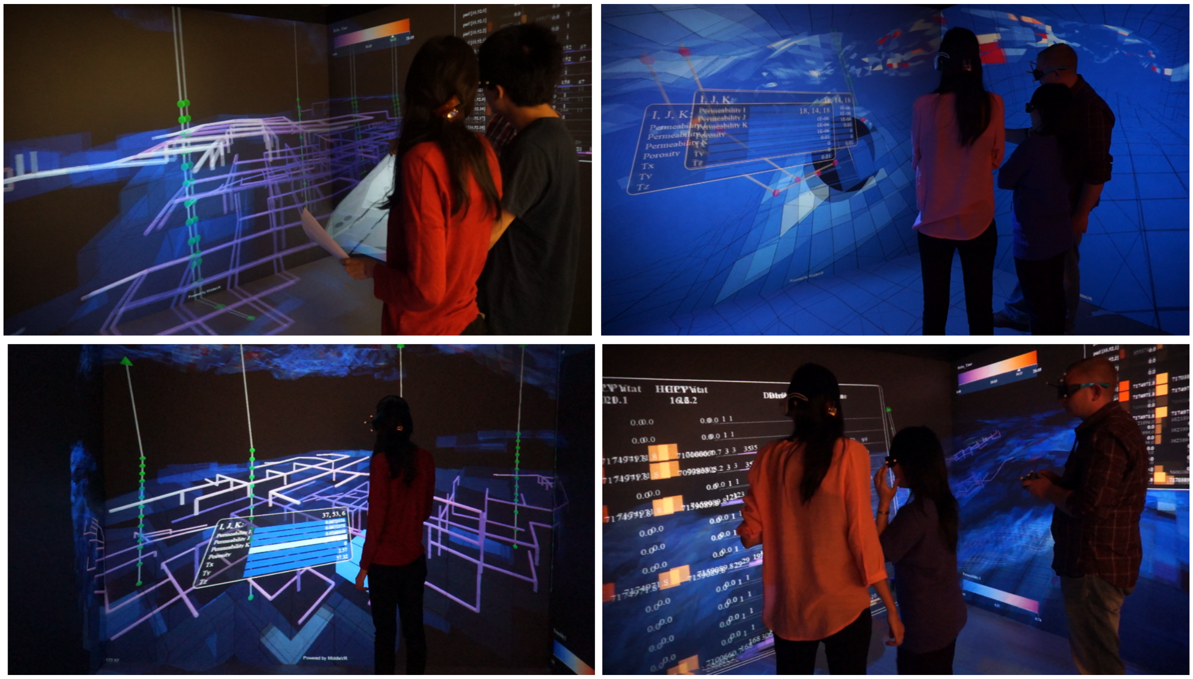

Figure 2.10: Visualizing reservoir connectivity [245].

2.7 Security Components

Security and privacy are related but separate concerns. In the context of this work, privacy is the ability for a user to have control over their information and how it is disseminated. This includes both personal information, and information that the user has access to and is responsable for within an industrial context. Security provides assurances that these user preferences regarding how information should be shared will be upheld. Although not sufficient to ensure security, mechanisims to provide confidentiality, integrity and availability of data or systems (the CIA Triad) are thought to be necessary conditions for information security [284]. A few of the security components that are discussed in this work are elaborated on here due to their importance in any system that hopes to provide security and privacy assurances.

2.7.1 Authentication

Authentication is the process of verifying the identity of an entity, typically a user. Once the identity of an entity is authenticated, then a system can decide if that verified entity is authorized to do

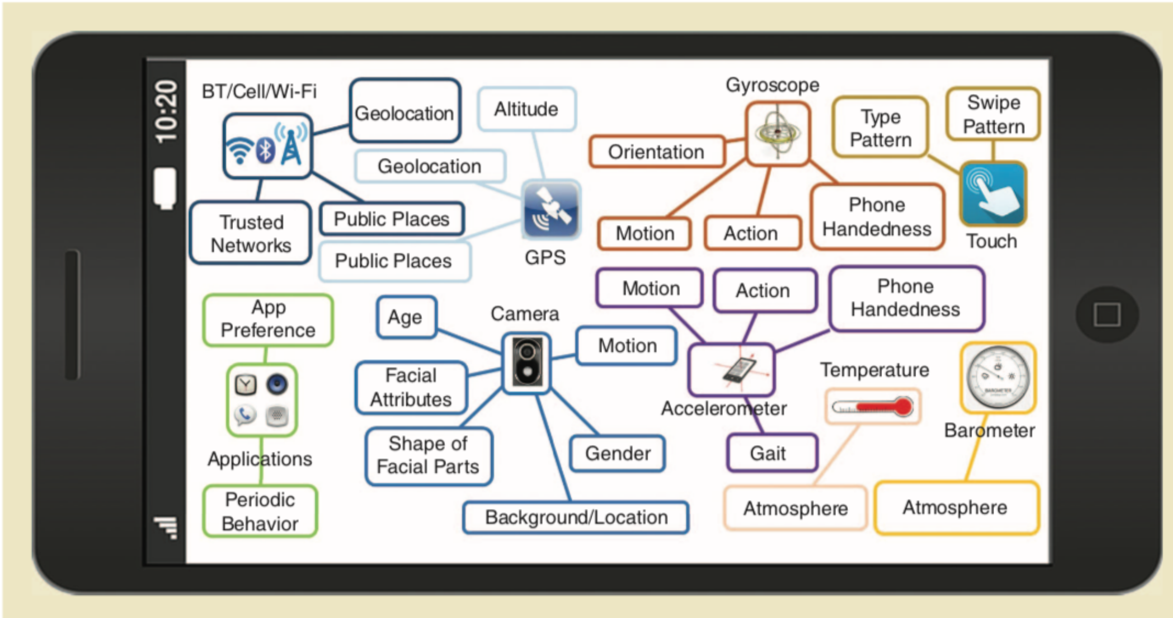

Figure 2.11: Examples of data used to continuously authenticate on mobile devices [237]

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some action such as join a collaboration session or access data. The first remote computer authentication scheme was proposed by Lamport [171] and required only a username and a password to access the system. Authentication has traditionally been accomplished by ”something-you-know”, ”something-you-have”, or ”something-you-are”. In a ”something-you-know” authentication system, users use a shared secret such as a password, gesture or pattern to authenticate. However if the shared secret becomes known to others, then they can falsely authenticate as the user. ”Something-you-have” authentication systems rely upon a physical item such as a token or device that is required to authenticate. The user can not be falsely authenticated by an attacker that knows a shared secret, however if the object is lost or stolen, then anyone in possession of the item may authenticate as the identity tied to the object. In a ”something-you-are” authentication scheme, then attributes of a user such as biometrics or traits of a user are used to verify the identity. The traits that are used may be physiological or behavioral. Since these attributes are a part of the user, they can not be easily lost unlike ”something-you-have” schemes. However they can be duplicated, and since they are tied to the user, a compromise can be difficult to contain, since the biometrics or traits can not generally be easily changed. Multi-factor authentication [232] combines various authentication methods, ideally across the different categories, to take advantage of the combined benefits of different approaches, while mitigating the disadvantages of the various authentication schemes. For example, if a ”something-you-have” scheme is combined with a ”something-you-know” scheme, then an impersonator must learn the shared secret and steal the item required for authentication, making the process much harder.

Continuous authentication schemes use one or more authentication mechanisims to continuously assess the current context, taking into account information such as user behaviours or biometrics and use this as basis to re-authenticate them periodically throughout a session [273]. A variety of continuous authentication methods have been applied to mobile devices [237], using various device sensors individually or together as shown in Figure 2.11. If sufficient information to ensure authorization is no longer available, the system will de-authenticate. This is more secure since it is no longer possible for another identity to use a session or device that has been left in an authenticated state. Also, since the authentication is formed based on constant re-assessment of the data, other factors can be considered such as location, other users present or data in the session at the same time to provide a context, of which the authentication is one piece of verified information. The formation of a context allows users to adapt to dynamic, changing environments, such as the addition of new data or individuals during a collaboration session. It is also more convenient, since users can more effortlessly work with a variety of devices and seamlessly move between them in a secure and convenient manner.

Although manually entering credentials such as passwords and PINs is still very common, entering this information when using immersive technologies such as head mounted virtual and augmented reality systems is clumsy and tiresome. For this reason, transparent authentication schemes are desirable since they do improve usability. Wearable authentication has a great deal of potential, despite being realatively unexplored [30]. In works such as ”A privacy-aware continuous authentication scheme for proximity-based access control” [6], the need to apply continuous and proximity based authentication to various scenarios has been recognized. For example, a framework for continuous authentication in ubiquitous computing environments has been proposed [56]. An example of a device that supports continuous authentication is the Nymi band [229], shown in Figure 2.12, which uses the rhythm of a users heartbeat to maintain an authenticated state [228]. Although this system could be ideal for virtual and augmented reality devices, it is not natively supported on Windows 10 Holographic at the moment, and is not usable on devices such as the Microsoft Hololens [211] for this reason. However, devices such as this allow authenticated sessions to be initiated and terminated dynamically supporting the continuous authentication, and context aware applications.

Figure 2.12: Nymi wearable is well suited for continuous authentication.

2.7.2 Access Control

Once a user has been authenticated to verify their identity, access control policy determines what exactly can be done using that identity, or what a user is authorized to do. An access control model is used to determine the proper relationship between subjects (entities that can perform actions) and objects (resources for which access should be controlled). A simple access control policy may be described in an access control matrix, as originally proposed by [173]

A key method of protecting information is by means of an access control system. The definition of high level rules or policies are formulated into a security model which is then used to determine if a given access request is to be granted or denied. This decision is then enforced by an access control mechanism.

The mandatory access control (MAC) model puts the control and management of access in the hands of the data owner instead of the end user by prescribing security labels to subjects and objects. Traditionally, lattice-based models such as Bell-LaPadula or Biba control the flow of information between the levels of classification [265].

Another form of access control policy is discretionary access control (DAC). In these models each object has an owner, and the access control is dictated by the owner, who may change the access to the object and allow or deny access based on an access control list, a group membership or other criteria available in the system.

Role-based access control (RBAC) [266] is also a common solution to access control. In role-based access control, access is restricted based on roles assigned to users. This is a very common method in many systems at the time of this writing. One limitation of RBAC is that roles are rigid. If a user is granted access via their role, that user gains access to the resource regardless of the situation. In many modern environments with ubiquitous computing and distributed collaboration, a more nuanced and contextually sensitive control system can help ensure that everyone has access to all of the data they need, but only the data they need for a specific purpose.

Moving beyond MAC, DAC or RBAC are access control models which are more suitable for a variety of complex situations that occur in modern computing environments such as dynamic collaboration contexts. One example that is increasingly being implemented in industry is Attribute Based Access Control [141]. Many others are primarily found in research literature but hold a great deal of promise. Some proposed access control policies that may have applicability to collaboration over sensitive data include access control policies that balance risk with trust [20], Team-based Access Control (TMAC) [306], Relationship Based access control [98], and Group Centric Access control [161].

Attribute-Based Access Control [124] [126] is a recent and popular approach to enterprise access controls that is well suited to dynamic and distributed systems. For example, compared to RBAC, ABAC is newer, simpler to implement in many environments, and accommodates real-time environmental states as access control parameters. It is adaptable and scalable to a wide variety of modern data-intensive contexts [52]. In a basic ABAC access control scenario, an access control decision is made using an access control policy, which takes as input various attributes defined by the system. These attributes can include environmental conditions (attributes), subject attributes and the object attributes. Once the policy is evaluated against these attributes, a policy decision is made.

Other access control policy models may be implemented using ABAC. For example RBAC may be implemented using an attribute based model. Due to the ease of administration and widespread familiarity with role based access control, a good solution may be to combine ABAC with RBAC [134]. Once roles become one of several possible attributes, the advantages of RBAC are lost since all the features of a RBAC system may be provided, while provding the flexibilty and control of additional attributes [59]. Although ABAC, does not naitively have provisions for context, privacy issues or trust relationships these may be built using ABAC attributes [335] [282].

Specifications for the comparison and evaluation of access control models [117] [125] have been developed. Attempts to develop a methodology for selecting access control models such as found in [26] or [137] have been proposed. Selection criteria includes the ease of administration, enforcement capabilities, performance properties and the support properties. Ease of administration can be dependent on the situation, as simpler access control methods are simpler to implement for the situations for which they are suited, but become difficult to administer when the scenarios become more complex. Important enforcement capabilities include the ability to uphold the principle of least privilege, support for delegation of access, separation of duty support and granularity of control.

In a survey of security-related research in ubiquitous computing [165], a number of requirements were identified for authentication and access control mechanisms in ubiquitous computing environments. These included adaptivity to context, or the ability to support users that move freely, and access services or information at any time. Access controls that can work on a context determined by various factors are more suitable for these scenarios. For this reason, context adaptive access control polices have been investigated for highly dynamic scenarios such as found when collaborating in pervaisive computing environments [310].

There are many considerations needed when implementing attribute based access control [123]. Although very flexible, ABAC can also be complex to manage and implement [126]. For this reason how and where to integrate the architectural components of ABAC must be decided carefully. How to manage attributes and how to articulate policy efficiently is also a key design consideration. In addition to the basic policy, attribute, and AC mechanism requirements, organizations wishing to implement ABAC must support management functions for enterprise policy development and distribution, enterprise identity and subject attributes, subject attribute sharing, enterprise object attributes, authentication, and AC mechanism deployment and distribution. Despite these implementation complexities, ABAC is getting traction as a real-world solution and is displacing incumbents such as RBAC due to its increased functionality and suitability for modern computing environments.

In order to describe the logic involved with the policy, a policy description mechanism must be implemented. For ABAC, there are currently two main standards used to describe ABAC policy:

XACML and NGAC.

XACML (Extensible Access Control Mark-up Language) [290] is an XML-based policy standard available since 2003. Although complex policy decisions can be described in the XACML access control policy language, poor implementation can result in performance problems during policy evaluation as well as errors in the policy logic which may result in information leakage. Techniques have been developed such as [222] which can parse and transform complex logical expressions in policies into decision tree structures, helping mitigate performance issues, as well as other policy management issues.

A newer option is Next Generation Access Control (NGAC). Both the XACML and NGAC standards support the expression and enforcement of vastly diverse access controls but differ with respect to the manner in which access control policies and attributes are specified and managed, and decisions are computed and enforced [95]. XACML and NGAC differ significantly in their expression and management of policies, treatment of attributes, computation of decisions, and representation of requests. Many of these differences stem from the methods with which they represent policies and attributes. XACMLs approach is to define policies by using logical formulas involving attribute values, while NGAC uses enumeration involving configurations of relations.

Chapter 3

Related Work

There are several themes that are related to the contributions of this work. The primary themes are immersion, reservoir engineering, collaboration and security. Immersion and its application to reservoir engineering has been discussed in the background chapter. Some previous works related to collaboration incorporating immersion will be discussed as this provides an overview of how immersion has been used to support collaboration. Although these works demonstrate examples of collaboration using immersion, security concerns are not addressed. Next, works that consider security in immersive environments provide an understanding of what has been done to provide security for immersive tools. These works do not apply the visual protection mechanisms used in this work and are not applied to reservoir engineering. A large number of these works are concerned only with augmented reality, and many do not consider collaboration. Mixed reality collaboration is discussed next, to show works that consider the security concerns when collaborating between virtual and physical worlds, although immersion is not necessarily utilized. These works show the confusion that can arise when working between shared spaces, especially between virtual and physical collaboration spaces. These works are important to this work, since they are directly applicable to the security concerns described when working between shared spaces. The next section describes some visual protection mechanisms, although most are not used in the context of collaboration or even immersion. These techniques are very important, however. These techniques have directly informed the design of the visual protection mechanism in this work. Finally, a variety of methods that could support collaborating over sensitive datasets rather than visual representations are presented. Although these works are less relevant as they apply to numerical data rather than visualizations, they inspired the concept of sharing partial information when collaborating. A comprehensive secure collaboration solution would likely have to incorporate these techniques.

3.1 Collaboration Incorporating Immersion

Collaborative immersive tools have been developed to support a variety of tasks related to many domains such as data visualization [79] [223] [149], mining [27] and engineering [319]. There are many other collaborative immersive applications emerging. CoVAR is a system that supports augmented reality and virtual reality collaboration [239]. This system uses two virtual cues to support collaboration awareness. A field of view cue shows the boundary of what other users can see through their display to inform others what they are looking at. The second is a gaze cue, showing the eye gaze direction. SharedSphere [180] is a system for sharing a view of a 360 video with a collaborator with immersive devices that also utilizes cues to communicate where users are looking. The DIGISCOPE project enables collaboration between large visualization infrastructures such as wall displays and CAVEs [97]. A preliminary framework for analyzing VR and AR collaboration across a variety of devices has been proposed [300]. The goal of this framework is to describe the technological configuration and interaction space used in a collaboration. None of these works address the security concerns of using immersive technologies for collaborating over sensitive data using a variety of technologies from the reality-virtuality continuum.

3.2 Security and Immersion

Systems such as Vampire Mirrors and Privacy Lamps have been proposed that allow users to use a natural means of understanding which obects are shared and which are private in immersive environments [46]. Shrestha et al. have provided an overview of attacks and defences on wearable computing devices including augmented reality devices [277]. In this work they consider the high level attacks and defences and provide some guidelines for security requirements to consider when using wearable technologies.

Augmented reality (AR) security has been discussed broadly in a variety of works such as [256]. In this work security and privacy challenges for AR have been organized along two axes: system scope and functionality. Functionality is categorized into output, input and data access. The authors consider these functionality challenges as they arise in three different system scopes: single applications, multiple applications and multiple systems. Examples of these challenges chiefly relate to the sharing of input and output devices in real time and the complex access controls that are required on sensor data. The authors note, however, that this is a relatively unexplored medium. Despite the challenges, there are many opportunities to address security and privacy in novel ways. Denning et al. [73] consider bystander privacy when using augmented reality glasses. They investigated the privacy perspectives of bystanders through semi-structured interviews of cafe patrons using a glasses-style AR mock up. This provided insight such as the greater perceived threat when using wearable AR devices due to the subtleness of recording using these devices and the desire to be notified and ideally even asked permission before recording. The authors discussed design considerations when using these devices and several potential design axes such as push or pull of privacy preference information, context awareness of proximity or location, and enforcement of strict policy rules related to the sharing or gathering of information rather than depending on a user or application to respect preferences. An example proposed by the authors is to use facial recognition to identify users, and then use that to determine preferences and obfuscate personally identifiable information such as their face in stored video. Issues around law and policy of augmented reality have been discussed [255]. These include the legal and policy issues around privacy, free speech, discrimination and safety. A world-driven access control policy has been proposed [257] that allows real-world objects to explicitly specify access control policies to mitigate the privacy and security concerns of augmented reality devices that are continuously gathering sensor data about their environment. This policy allows functionality such as deactivating sensors or video recording depending on location or proximity to physical objects, and providing notifications to the user of the AR device. PrivacyManager [183] is an access control framework for augmented reality applications that considers various contextual factors such as location, network signals, ambient light, sound, and other inputs. Based on these factors, sensors such as the camera or microphone on an augmented reality device may be disabled. Lebeck et al. have developed an augmented reality platform called Arya [177] that secures the augmented reality output displayed to the user according to a policy framework. Objects to be displayed have attributes that are used for policy decisions and attributes can be related to the visual properties of the AR objects or the relationships between the AR objects and other virtual or real-world objects. It has been proposed that user-driven access control is a way to manage the complexity of user permission mangement and prevent negative effects such as prompt-fatigue [254]. User-driven access control uses the way that users naturally interact with applications to gather permission-granting information. The authors note that platforms such as augmented reality minimize direct user interaction with applications, presenting unique challenges when designing systems that utilize user-driven access control.

A variety of works have considered how to authenticate users in immersive devices. Yu et al. [334] attempted to provide usable authentication systems for virtual reality by exploring a variety of authentication mechanisms. They examined PIN codes, 2D patterns and 3D pattern passwords. Although the 2D methods were easier for the user, they were also the easiest to guess by watching videos of the VR user authenticate. George et al. also studied PIN entry and 2D patterns as authentication mechanisims in virtual reality [104]. They note that PIN and pattern entry pads presented in VR provide greater security from shoulder surfing attacks than traditional devices due to a private visual channel. However, they report an 18% success rate of observational attacks when entering credentials by these means. A continuous authentication scheme that makes use of the eye movements of immersive headset users has been developed [341]. Although there is often an assumption that there is no leakage of information from the private visual channel, it has been shown this is not always the case [156].

The Looks Good to Me (LGTM) protocol [102] has been developed to act as a usable and secure authentication protocol for augmented reality using facial recognition and wireless location, specifically designed for sharing information in augmented reality. Holopair [281] proposes a protocol to securely pair Microsoft Hololens devices. The authors of Holopair introduce the concept of a secure visual channel that can be used in addition to the wireless network channel to provide authentication. This protocol takes advantage of the fact that different users can overlay unique information over their view to send an authentication pattern to a user that they wish to pair with. Combined with the use of the wireless channel to transmit data such as public keys, they are able to authenticate the user of their choosing and then communicate securely. Further to this, they claim that shared collaboration that includes holographic and real-world objects is core to augmented reality applications and calls for secured connections between users.

Although very generalized, a review of security related research in ubiquitious computing [165] reveals several insights relevant to collaboration in a dynamic virtual and augmented reality setting. These include identification of requirements for authentication and access control in ubiquitous computing environments. There is a need for context-aware access control not provided by access control policies found in traditional distributed environments such as role-based access control (RBAC). Context-aware policies that can at least consider time and space dimensions are suggested. Policies must also be adaptable to users behavior and capable of assigning attributes based on their behavior and able to manage trust relationships. Dynamic recognition of users is also desired either through identity based authentication, such as biometrics, or other means, such as those based on reputation. Non-intrusive authentication mechanisms that provide continuous, unobtrusive authentication are ideal. They also outline a variety of privacy protection mechanisms, such as masking of identification, limiting of actions based on proximity, building proximity based trust relationships, consent negotiation for recording of information, and obfuscation of information by degrading the quality of information.

A survey of access control models for pervasive environments [86] considers various proposed access control models for scenarios where traditional approaches such as Mandatory Access Control (MAC), Discretionary Access Control (DAC) and Role Based Access Control (RBAC) are not suitable. These access control methods are better suited to traditional centralized and static environments where the subjects and objects are known and relatively static and permissions do not change frequently. They consider four classes of access control models: context-aware, attribute-based, user behavior-based and relation based.

There is a substantial amount of work exploring security and privacy in immersive environments. Much of this work is focused on securing augmented reality systems. There is also a fair amount of work around authentication methods in immersive environments. Many works can be found related to determining appropriate access control policies for dynamic, contextual situations. There are few works that address the security concerns of using immersive environments for collaboration over data.

3.3 Mixed Reality Collaboration and Security

There are some works looking at security and privacy in collaborative environments consisting of both physical and virtual worlds. Although these are not focused on immersive technologies there are some similar concerns, especially when integrating a variety of platforms such as augmented reality and virtual reality.

SecSpace [250] is a toolkit for usable privacy and security in mixed reality collaborative environments that combine physical and virtual spaces. Privacy-related actions may be performed in either virtual or physical space and generate effects simultaneously in both spaces. Mixed-presence systems try to achieve fluid collaboration between remote and co-located users, however this can make it difficult to understand how actions in one location are manifested in the other location. Privacy and security must be managed across both the physical channel amongst co-located collaborators and the virtual channel to remote collaborators.

Further explorations of collaboration in mixed reality consisting of a physical and virtual environment were performed [262]. In this work, two scenarios were considered involving hiding and sharing virtual documents around a tabletop. In one, a solo display showed the remote collaborator as an avatar. In the second scenario, circumambient displays showed the rest of the connected virtual environment. Four cues were explored: interactive, communication-based, ambient and infrastructure. The authors look to blended interaction [133] to enable cooperative workflows that integrate physical and digital environments, while maintaining the primacy of physical actions in co-located collaboration when using the digital tools and services. From this paper, it is clear that when there are mixed virtual and physical environments, it is important to make sure that users can clearly understand what is viewable by other participants. It is important to help collaborators understand how behaviors in one environment are reflected in the other environment. Participants were also very interested in understanding how they were presented to remote collaborators.

3.4 Visual Security Controls

Typically, access to information is provided on an all-or-nothing basis, depending on whether the user successfully authenticates at the beginning of a session. This ignores the fact that tasks performed during a collaboration may have a range of sensitivities, depending on the nature of the data and the context. For this reason access control methods must be developed that allow for partial disclosure of information. In many visualization contexts, there is value in seeing context without focus or conceptual views of information, rather than high fidelity views.

One common method of applying security in a visualization context is to limit the information leaving a central server. Traditionally this means that only image based visualization tools are possible on clients, however more innovative techniques have been developed to prevent data from moving to clients, while still allowing for greater interactivity than image based tools.

As an example Rixels [9] is a technique that renders ”rich pixels” by perform much processing on the server, however there is still sufficient detail due to the attributes of the rich pixels to instantly perform post-processing operations also on the client to reduce bandwidth and improve the interactivity. Due to the processing steps on the server, the amount of information that is transmitted is limited. However, a fundamental problem still exists. Although many technologies protect data at rest or in transit using tools such as encryption, less thought is given to how to protect the information that is displayed on screen. In a study commissioned by 3M, this visual security was identified as often ignored yet important to the enterprise security ecosystem [307].

Attempts have been made to prevent leakage of visual information. Web browser privacy blinders have been developed [302] that hide some sensitive information while allowing other less sensitive information to be viewable. For example [343] designed a tablet that detects when other are looking at the screen and provides awareness using glyphs.

Visual protection mechanisms that alter the scene of an image or video to prevent inadvertent sharing of sensitive details in media such as video or digital photographs have been proposed [235]. A large focus of these works are to remove identifiers from content so that privacy may be protected, while still sharing media. These include blurring or blocking of marked sensitive regions [187] [247], cartooning [118] [336] or painting [295]. Ribaric et al [252], for instance, describe a variety of techniques to alter media to remove personal identifiers. Identifiers may be non-biometric, physiological and behavioural biometric, and soft biometric identifiers. This can include the removal of information such as tattoos, modification of facial data to make it difficult to re-create an accurate face model, or scrambling of identifiers. Multimodal de-identification methods that simultaneously hide, remove or substitute different types of personal identification are also needed to protect privacy of individuals.

Although these methods to protect identifiers are a very different application than protecting data during a collaborative sensemaking scenario, the core of the problem is similar. When considering a collaboration scenario involving data, the need for protection of sensitive or revealing attributes of the data is essential when collaborating with users that have different levels of access to the data.

Another approach that is similar combines obfuscated and visible data for the benefit of the user [158] by blurring areas that are not important so a user may focus on areas of interest. This is quite different than visual protections, which focusing on reducing the fidelity of sensitive content, while providing some contextual information. However, it does provide a similar overall mechanism, although with a different goal.

3.5 Other Security Controls

Other techniques that are not directly related can be relevant. One exmaple is anonymizing datasets using methods such as k-Anonymity [297]. Differential privacy methods allow datasets to be analyzed and results to be used for machine learning techniques [2] while maintaining privacy of the training datasets. This kind of separation between the raw data and the results of actions performed on the data may be leveraged to provide useful information to those with restricted clearance. DataSHIELD [328] is another approach to sharing sensitive information by allowing the analysis of sensitive individual-level data from one dataset, and the co-analysis of this data from several studies simultaneously without physically pooling them or disclosing any data. Technologies such as these ideally would work together with visual protections to provide a comprehensive solution for collaborating over sensitive data.

Chapter 4

Immersive Reservoir Visualization Tool

This tool was developed in collaboration with Emil Selin, Steven Samoil and Roberta Mota.

A prerequisite to validating security features is a tool that is usable for collaboration over reservoir data. This chapter describes the design considerations, features and feedback regarding this tool. With the tool in place, the next steps are to understand some of the collaboration scenarios in which it may be used, understand the risks in these scenarios and then consider possible security features. From here a potential solution may be implemented, and an evaluation performed to determine the quality of the solution.

The immersive tool provides reservoir engineers with a tool for analysing 3D reservoir data using augmented and virtual reality HMDs and a CAVE. The complicated 3D datasets and analysis required to support reservoir engineering provide an ideal use case for immersion. Improved spatial perception allows users to rapidly understand the nuances of 3D reservoir models. The variety of interaction mechanisms have the potential to contribute to more natural interactions that help users focus on the task rather than the interface, if designed properly [227]. The increased working space will allow models to be visualized at human scale, allowing for easy analysis, and data may be displayed without cluttering up precious screen space. The ability for collaborators to leverage these benefits together in real-time as collaboration capabilities are added also provides benefit since input from a variety of professionals is typically required throughout the exploration, development and production cycles.

4.1 Overview

The oil and gas industry has long used visualization to help analyse the large, complex datasets that are commonly encountered in this field. Early attempts at immersive applications were regarded as promising, however several factors were identified by Kinsland and Borst that prevented immersion from fulfilling its promise [152]. In order to provide a modern platform for investigation of secure collaboration, a reservoir engineering tool was developed for analysing reservoir data in an effort to utilize modern hardware, while also attempting to mitigate the factors that were reported to hinder adoption in previous immersive tools for reservoir engineering.

The factors identified by Kinsland and Borst included:

1. Interruption of typical user workflow to leave the comfort and convenience of their desks for large, centralized immersive hardware such as CAVEs which were the predominant hardware platform for immersion in previous reservoir engineering tools;
2. A lack of compatibility with existing software that users were familiar with;
3. The need for specialized help to be available to run the immersive hardware whenever a user would like to use it;
4. Vertigo when using immersive systems;
5. Lack of user acceptance on the part of domain experts; and
6. Lack of well developed interface hardware and 3D user interface design that provides a high quality user experience.

Kinsland and Borst provided some very useful information for the design of this tool, and motivation for developing it. Since immersive technologies have previously been applied to the oil and gas industry without widespread adoption, there is a risk that another immersive tool is not worth developing. In fact during initial consultations for the development of this tool, many experts referenced the previous failures of immersive technology and suggested that immersion was not worth the effort and the development of another immersive tool would be futile. However, the analysis by Kinsland and Borst provided a useful retrospective on what had gone wrong. Their list of factors that prevented adoption of immersive tools in the oil and gas industry provided guidance and confidence in the long term potential of immersive applications for the oil and gas industry.

The availability of vastly improved immersive head mounted displays that may be used on computer systems commonly found in professional environments mitigates several of these factors. For no more than the cost of a high quality monitor, head mounted immersive hardware can be purchased off the shelf and used on user workstations that have sufficient graphics capabilities. This allows users to utilize the benefits of immersion at their workstation, without having to move their work to another environment. These commodity head mounted devices are easy to use and allow the user to be self-sufficient with minimal training. Further to this, data from commonly used tools can be converted into formats readable by the tool presented here. This process could be automated to provide inter-operability with existing software, making the immersive tool even easier to use. Central infrastructure such as CAVEs may still be utilized by ensuring that tools that work on the head mounted displays can scale up and work on the large scale environments, providing a means to shift the work from the HMD to these environments as required for group demonstrations or collaboration. These large scale environments are also much easier to use due to greatly improved hardware and software, allowing users to make use of them without specialized expertise except when issues arise. Due to this, moving between the head mounted display and the the large scale environment may be no more difficult than moving a presentation from a 2D screen at a workstation to a large 2D screen for group collaboration. Both the head mounted displays and the large scale facilities have benefited from advances in technology, showing improvements not only in performance and ease of use but also comfort. Improved hardware and software has improved graphics frame rates, reduced tracking jitter, improved rendering of the correct perspective and reduced optical distortions. These improvements reduce discomfort in many users. Further to this, a variety of software techniques are emerging to reduce discomfort even in those that still tend to experience it despite improved hardware and immersive systems [94] [167]. Given the large amount of investment in immersive hardware and software at the time of this writing, it is likely that immersive platforms will only become more visually appealing, comfortable and easy to use. For this reason the first four factors that were identified by Kinsland and Borst as hindering adoption of immersive technologies are largely resolved and will only continue to diminish over time, especially as new technologies emerge. Regarding lack of acceptance by domain experts, Kinsland and Borst suggest that as the hardware and software improve, the benefits will become greater and drive adoption.

In order to overcome the final limitation (i.e. the lack of effective interfaces and interaction techniques for 3DVR) the tool was built from the ground up with continuous feedback from subject matter experts in reservoir engineering. Many previous attempts to provide immersive tools for reservoir engineering simply tried to extend desktop applications directly into a 3D environment. Sometimes this would be done quite literally through the use of OpenGL interceptors such as Mechdyne Conduit [207] or TechViz XL [304]. This approach intercepts the OpenGL calls and then uses these intercepted calls to provide an immersive experience in an environment such as a CAVE. Although this is a tempting method to use since it shows a desktop application in an immersive environment, it does not provide a high quality immersive experience due to some aspects of the desktop experience invariably becoming compromised during this transition and the inability to provide a high quality experience due to the use of an application designed for 2D in a 3D environment [216].

Utilization of relevant design principles should help with the development of an effective and useful tool. For example, immersive environments, if designed carefully, can provide intuitive applications that naturally support Reality-Based Interaction [131]. This should improve how easily a user can maintain an accurate mental model when using the application, thus reducing the gulf of evaluation (The difference between the state of a system and the users perception of that state) or gulf of exection (he difference between the allowable actions of a system and the users intentions for using the system) [226]. The immersive application implements several techniques that fit within Reality-Based Interaction themes such as the use of body awareness and skills. Immersive applications are realatively easy to align with Reality-Based Interaction principles. Due to their highly interactive and spatial nature, immersive applications can be built with the users pre-existing knowledge of their non-digital world in mind to create a tool that is intuitve to use.

Elmqvist et al. have proposed a set of design guidelines to promote fluid interaction in information visualization [85]. According to Elmqvist et al., “Fluidity in information visualization is an elusive and intangible concept characterized by smooth, seamless, and powerful interaction; responsive, interactive and rapidly-updated graphics; and careful, conscientious, and comprehensive user experiences.” Fluid interactions are thought to help users stay in a state of flow [62] as they perform their work. Flow is a mental state of total focus on an activity, that enables greater productivity and enhanced user experience. Their design guidelines have been followed whenever possible in this application. For example the guideline ”minimize indirection in the interface” is applied by utilizing direct manipulation and embodied interactions. Fluid interactions are realatively easy to support in immersive environments since a variety of interaction possibilities are possible, both natural and magical, and immersion can lead to increased engagement and focus [329]. Conversely, ensuring that an immersive application utilizes the principles of fluid interaction can ensure that immersion, and engagement remains high.

4.2 Features Implemented

The tool facilitates analysis of the structure and static properties of oil and gas reservoir models. Three occlusion management methods were implemented that help examine property values of internal cells and understand the spatial orientation of structures in the subsurface. At the time of this writing, these methods are unique in their application to immersive reservoir engineering tools. The tool was presented to a variety of oil and gas professionals, researchers and students. Feedback was collected with a focus on three primary themes. First, the value of immersion for analysis of static reservoir properties. Second, the effectiveness of the occlusion management techniques. Third, assessment of the contribution of the interactions implemented to promoting periods of focused concentration known as flow. This will serve as a platform in which a variety of questions around the use of immersion and 3D user interfaces in a professional engineering domain may be explored.

This tool has parallels with a tool developed by Cabral Mota et al., who developed a tool for immersive analysis of fluid flow connetivity [245]. This tool visualized static reservoir data and used mathematical graphing algorithms to determine where fluid would flow based on transmissibility, which is a measure of how readily fluid will flow between points. A mathematical graph would then be visualized within the reservoir model to provide a visualization of the fluid flow connectivity between regions based on the transmissiblity metric. A transparent lens was attached to a controller or hand to overcome occlusion and provide a clear view when probing into the reservoir data to help understand property values affecting the fluid flow. The application that was developed for this work lacks the connectivity analysis and transparent lens techniques of the tool developed by Cabral Mota et al, but provides a variety of different interaction and occlusion management techniques and is focused on understanding how professionals can gain value from the technology when performing analysis of static reservoir data. Additional features such as visual analytics capabilities, support for dynamic data and flow visualization will also be implemented.

When considering a reservoir model, there are a variety of analysis tasks performed. One common task is to perform inspections of embedded structures, such as wells, within the subsurface and visualize how they interface with the geology around them. The reservoir data must also be inspected to understand how areas of the reservoir interact when hydrocarbon extraction is occurring. Typical analysis involves searching for deficiencies in the geological model or regions of interest that may benefit or impede production. Common to all these tasks is that they require a user to understand the properties of specific cells within the model, while keeping in mind the greater context of the reservoir structure such as layers, relative spatial location to wells or faults, and the form and location of specific geological features that affect production.

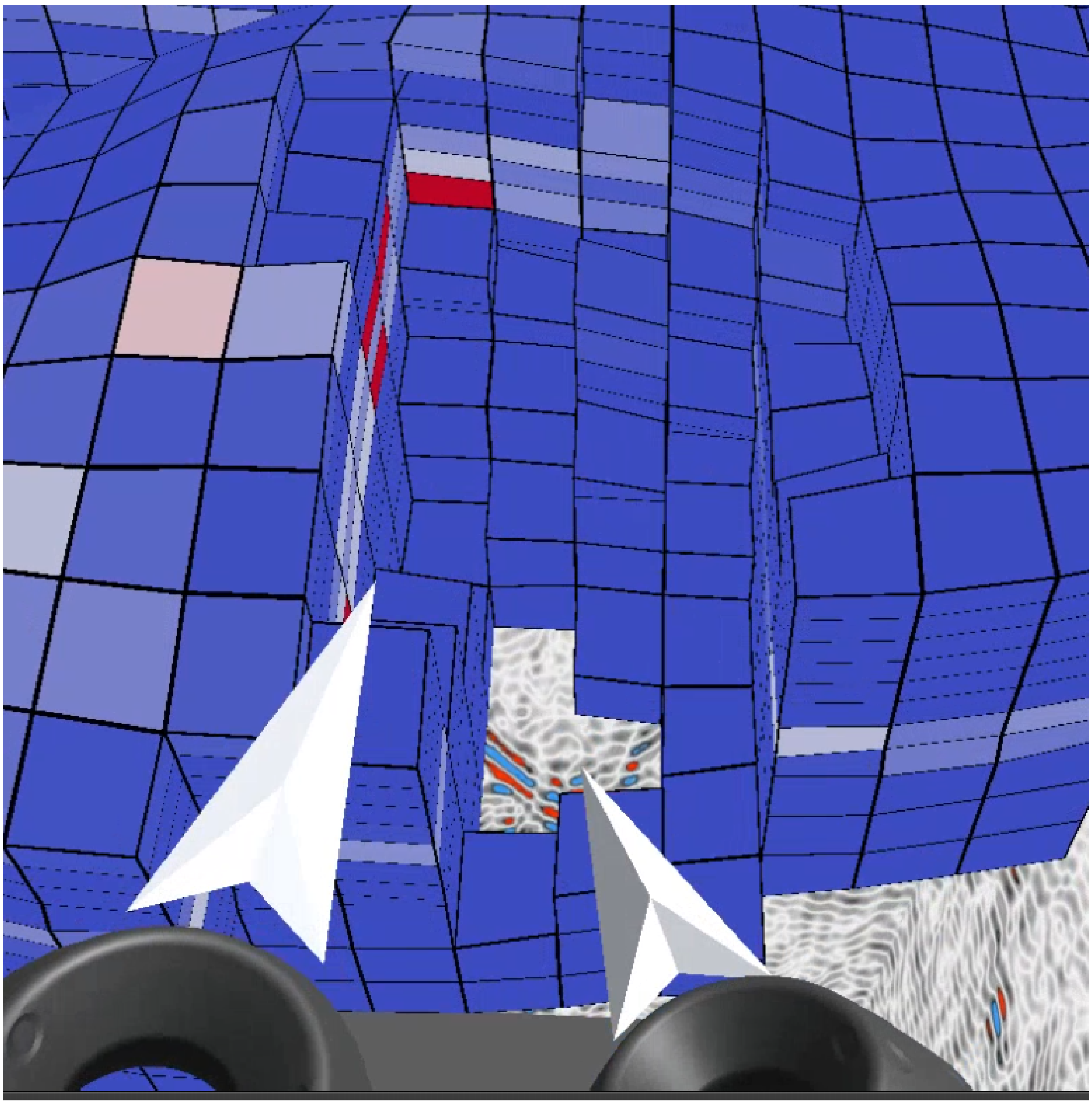

Figure 4.1: Digging into the model.

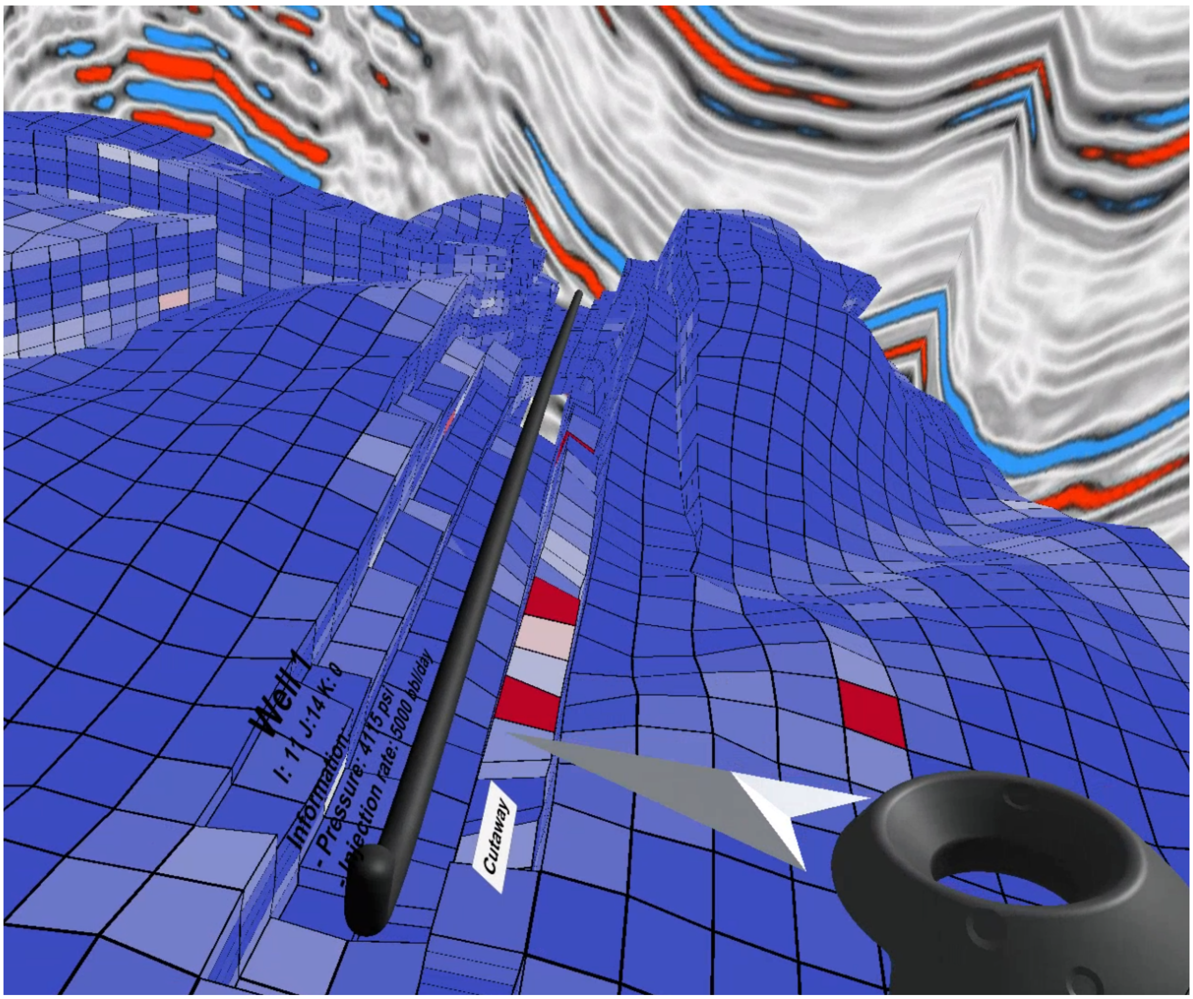

Figure 4.2: Cutaway view of embedded object.

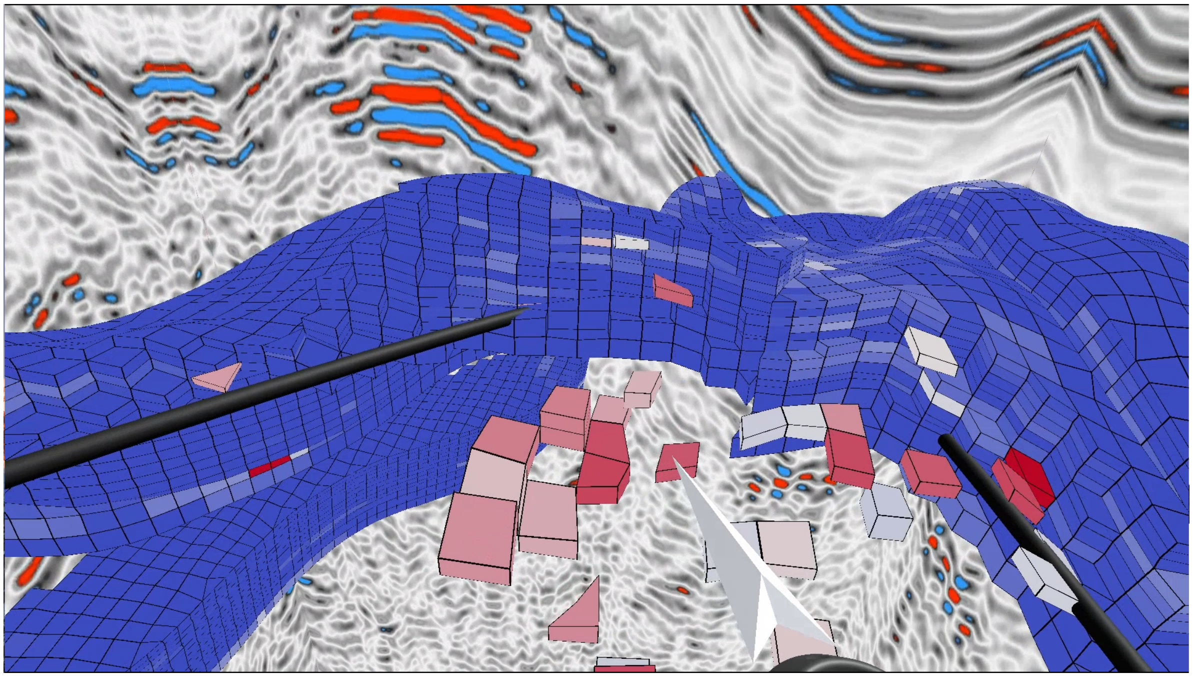

Figure 4.3: Embodied filter sphere.

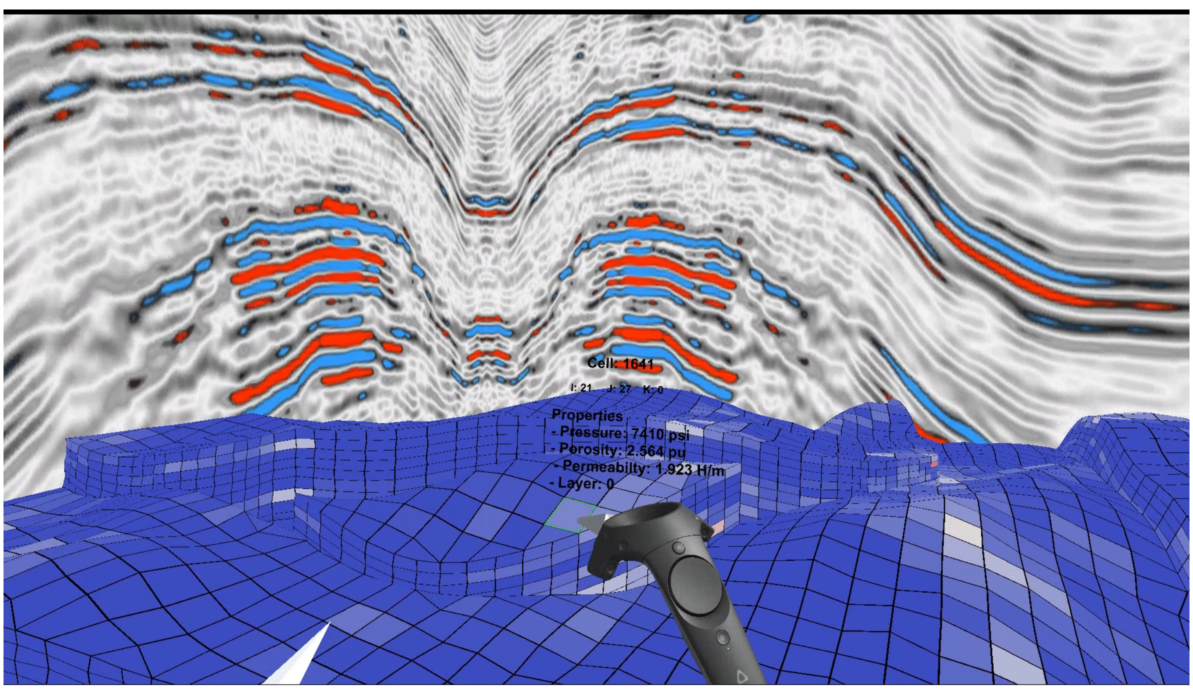

Figure 4.4: Examining the reservoir.

The application visualizes the volumetric structure of the geological model of the reservoir providing a colour mapping for a selected property. An example property is porosity, an indicator of the relative volume of empty space in the form of pores to solid material. In the pictures shown, porosity is the value used, with red indicating high porosity values and dark blue representing the lowest porosity values in the dataset. Seismic data may also be shown in the model, providing further context.

One fundamental challenge with the visualization of 3D data is occlusion. A cutaway style embodied filter was implemented that allows a user to inspect cells of interest or embedded structures, such as wells, within the volumetric dataset. This technique attaches a filter around the users head so a user can inspect cells of interest or embedded structures such as wells within the volumetric dataset. If it is desirable to maintain a specific view, the embodied aspect of the filter can be turned off, keeping the filtered view in place.

The embodied filter facilitates analysis of the static properties of cells embedded within the geological model. Cells meeting a certain criteria such as a range of property values can be selected and cells not meeting this criteria are filtered out of a sphere radiating from the users viewpoint. As a user moves around the geological realization, the filter is applied to cells within the sphere, providing an interior view and revealing embedded structures while preserving the cells that are of interest. This permits a user to see how the data relates to these structures, while ensuring that the needed context of the geological structure is preserved. The user can probe and get detailed information about specific cells. The use of a filter tied to head tracking enables a user to explore the dataset with a minimal use of hands, only probing when needed. This reduces fatigue over long analysis sessions. The diameter of the filtering sphere can be adjusted to give more context or a wider view into the interior of the geological model as needed.

Another means of viewing the embedded structures is to open a cutaway view to reveal them, by selecting a cutaway button on the exterior of the geological model. This reveals the embedded structure, while maintaining a view of the neighbouring geology and the overall context of the entire geological model. As a means of either editing the geological model or removing occluding cells the controller can be used to remove or add cells to the model. The user may dig through the geological model to reach the interior.

A menu may be summoned by pressing a button on the controller, enabling seismic data visualization, adjustment of the height of the geological model, the radius of the filtering sphere and the threshold of the value to be filtered. There are also functions to reset the model by reinstating any removed cells and to select if the filtering sphere should be frozen in place or follow the users perspective.

4.3 Evaluation

The application was presented to over 40 oil and gas professionals in a variety of venues such as the group visualization centre (the Energi Simulation / Frank and Sarah Meyer Collaboration Centre [251]), industry events, conferences and oil and gas company offices with the intention of determining the level of interest in immersive applications within the oil and gas industry and determining the effectiveness of the techniques in the application.

Since the tool was often demonstrated as part of events or conferences, or to group tours at the Collaboration Centre, there was often not the opportunity to perform an extensive feedback session. However, a large number of subject matter experts were exposed to the tool during these events, so a lightweight, informal evaluation protocol was prepared for obtaining feedback. This consisted of providing enough time to learn the interface and understand the application. Then, as long as there was enough time, feedback would be gathered to determine: (1) If the immersion assists engineering professionals with understanding the static data, especially compared to non-immersive desktop applications, (2) Which of the three occlusion management techniques are preferred, (3) If the application helps ensure a state of flow so that users can focus on the task without breaking concentration to focus on using the application. In pursuit of these objectives, the following questions were asked:

1. Have you analysed reservoir models before?
2. How did you perform this analysis?
3. How does the application compare to your current methods of analysis?
4. Do you find that this application provided any benefits over current methods of analysis?
5. Compared to existing methods, did you find that you were able to spend less time using the interface and more time focusing on the goals of the analysis?
6. What do you not like about using the tool?

Figure 4.5: User evaluation.

Figure 4.6: Gathering feedback.

4.3.1 Theme 1: Value of Immersion

All users reported that immersion provided a very good understanding of the subsurface realization. This was due to increased understanding of spatial relationships, such as orientation and depth of a fault within the subsurface, or the relative distance of wells to geological features. The ability to move through the reservoir using a natural action, such as moving around a room, exploring different sections of the reservoir and using controllers to manipulate or probe cells directly was reported to be easy to learn and intuitive. The increased field of view and field of regard were reported to be very beneficial when trying to maintain context especially when users were situated within the data. Seeing the entire reservoir at a glance and then having the ability to do detailed analysis from a variety of views was reported to save time. When using 2D applications many users reported that they must move between several 2D views of the dataset. Switching between these views can be time consuming and requires professionals to maintain a mental map in their head, increasing cognitive load and the chance of error. With years of practice, this can become second nature for experts, however this is still a fallible process that even experts admit can lead to errors if the mental map is conceptualized incorrectly. It was observed that users were able to accomplish analysis of cell properties and relationships of cell regions with wells and other regions with very little training using the application, regardless of experience.

Over half of the oil and gas professionals interviewed saw the advantages, but reported that they were not convinced that the advantages of virtual reality would encourage them to use immersive applications in their day to day work. However, there is a portion of oil and gas professionals that would consider using such a tool, if it was easy to use, did not require extensive re-training and provided the same features as 2D applications.

4.3.2 Theme 2: Occlusion Management

Users were given the opportunity to try the three different occlusion management techniques and provide feedback on how effective they found these techniques. The three techniques were 1) a digging technique, where the controller is used to remove cells, 2) a cutaway view of embedded structures such as wells, and 3) a spherical cell filter that moves with the users head.

The digging method removes occluding cells to create views of the interior. This is the most destructive method. Users found fine control of cells to be removed very beneficial in situations where this fine detail was required, such as optimizing a view by removing a small number of cells, or uncovering a specific structure, such as a well head, while leaving the majority of cells intact. One limitation that frustrated users was the lack of an easy way to keep some cells that are of interest when removing others. If some cells need to be preserved, users must dig very carefully or miss information. For this reason the technique was not found to be efficient for working on a large number of cells or across a large area.

The cutaway view was seen as useful in some circumstances. Looking at the path of a well, or getting a sense of the property values in a critical region around an embedded structure was easily accomplished using this feature. With deeply embedded structures, however, a large amount of context could be lost.

The embodied filter was extremely well received. Virtually all participants mentioned this method as their favourite occlusion management mechanism. The mechanism of being able to move back or forward through physical movement to move between a full view of an area and a filtered view was seen as very intuitive and helpful. Since it applied a filter and did not simply remove cells, users liked that it could reveal areas within the dataset, while still allowing them to reference cells of interest that were outside of the filter parameters. A common way that this interaction was used, was to scan the dataset for areas of interest, and then freeze the filter view, and do detailed inspections with a combination of probing to inspect cells and digging as required to remove a small amount of cells for detailed exploration of smaller regions of data.

4.3.3 Theme 3: Maintaining Flow

To determine if the use of Reality-Based Interactions and guidelines to promote flow were successful in engrossing the user in the application and promoting uninterrupted focus. Users were asked if they felt that their concentration was broken when interacting with the application during the task, and if the application provided the opportunity to focus on their objective. Users were also asked for a comparison to the desktop applications they use. Although there are some menus in the application, once the user has set the radius on the filter sphere and parameters such as the height of the dataset, they are able to scan for areas of interest and analyse these areas carefully without feeling a loss of focus. Most users reported that natural movements such as walking or head movement to get different views combined with increased perceptual advantages meant they were able to focus on the analysis and maintain a mental map of the data in their head more easily than using 2D software.

4.3.4 Conclusion

Based upon evaluation by many subject matter experts over time, this prototype tool demonstrates the potential of modern immersive applications for the reservoir engineering domain. Immersive environments provide interfaces that allow users to interact in a variety of ways compatible with frameworks such as reality-based interaction and guidelines such as fluid interaction. Combined with the visual benefits of immersion such as a wide field of view, large working space, and increased spatial perception, immersive environments can provide tools that are intuitive and effective for dealing with the complex 3D information encountered in reservoir engineering. The development of this tool for visualizing reservoir data and analysing well placement has allowed an immersive application for reservoir engineering to be demonstrated to oil and gas subject matter experts on modern immersive hardware. There was some resistance to the immersive application due the historic inability of immersion to gain widespread adoption within the oil and gas industry. Many of the factors contributing to lack of adoption are mitigated by the increasingly cost effective and high quality immersive devices that are now available. The remaining factors can be mitigated by supporting user needs with careful design of interactions that leverage the strengths of immersion to provide highly interactive and effective applications that adhere to interaction best practices.

Upon spending time in the prototype tool, many users appreciated the benefits of immersion, and were often surprised at the quality of the hardware and the interactions. The interactions were reported to be intuitive and effective for analysing the reservoir data. Users particularly liked the ease in which they could form a mental map of spatial relationships between different regions of interest and wells. The occlusion management techniques were all reported to be very useful, although each was ideal for a different purpose. The digging interaction provided a method for fine-grained removal of smaller quantities of cells. The cutaway method was very useful to reveal embedded structures, such as wells, and to quickly scan for important features or data relevant to these structures. The embodied filter received positive feedback from virtually all users. This interaction was reported to be ideal for exploring reservoir data and rapidly building a mental map of its structure. As hypothesized, the highly spatial and interactive nature of immersive environments are conducive to reality-based interaction and fluid interaction, with most users reporting that they were able to maintain a high degree of engagement and focus on the analysis of the data.

While these evaluation sessions are not definitive or even rigorous, they allow for insight into the viability of such a tool, and provide an indication whether further development of this tool should be pursued, if a redesign is needed, or if this an altogether futile path of investigation. Fortunately, feedback was generally positive, and suggests that further development of the prototype is worthwhile.

4.3.5 Collaborative Capabilities

After validating that the tool and the interactions provided value to users in the reservoir engineering domain, collaborative capabilites were added. The current implementation supports collaboration between the HTC Vive, Oculus Rift, Microsoft Hololens and a public display. There is a simple representation of an avatar for each collaborator, and users can work together on separate devices. Co-located collaboration may also be achieved in a CAVE [69]. It is possible to take work from HMD devices and display it in the CAVE for presentations or collaboration. These environments are semi-immersive since users can still view their environment through lightweight stereoscopic 3D glasses. This provides a comfortable means of working with an immersive application since users are not isolated from their environment and can still have a sense of interpersonal connection to others in the same physical space. Although the classic styled CAVE does suffer from compromised collaboration due to a single optimal view perspective [240], users report an acceptible collaboration experience by staying close to the user with the optimal view perspective so that they have a similar perspective. The weakness of the single optimal view perspective may be also mitigated though effective management of the view perspective [88]. More recent large-scale immersive visualization systems have emerged such as the CAVE2 [92] which can provide correct stereo perspective for multiple users using omnistereo [279]. Multi-user stereoscopic environments have also been implemented using specialized projectors [164].

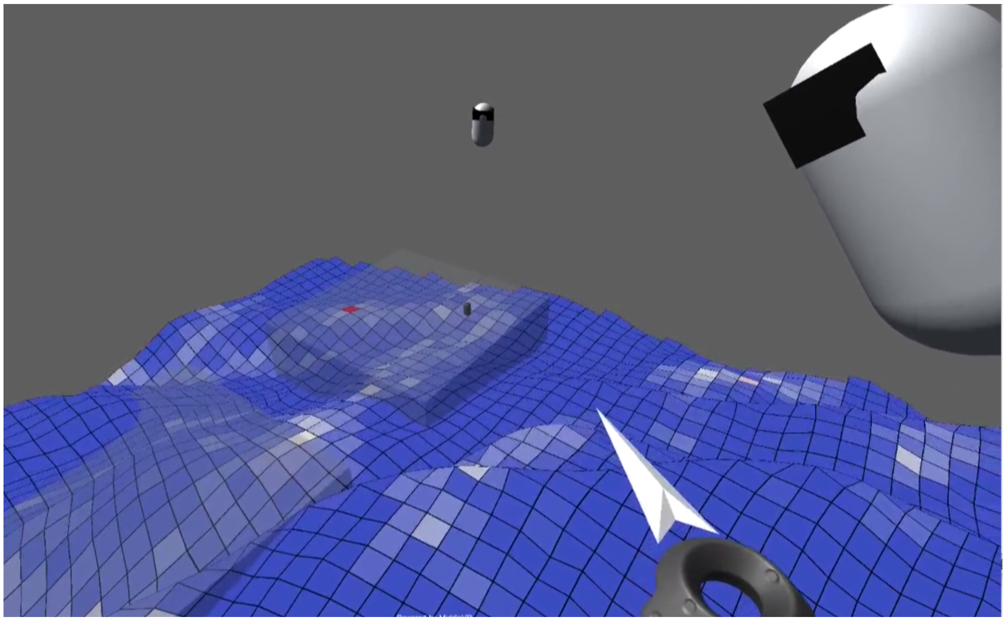

Figure 4.7: Collaboration using head mounted devices and avatars.

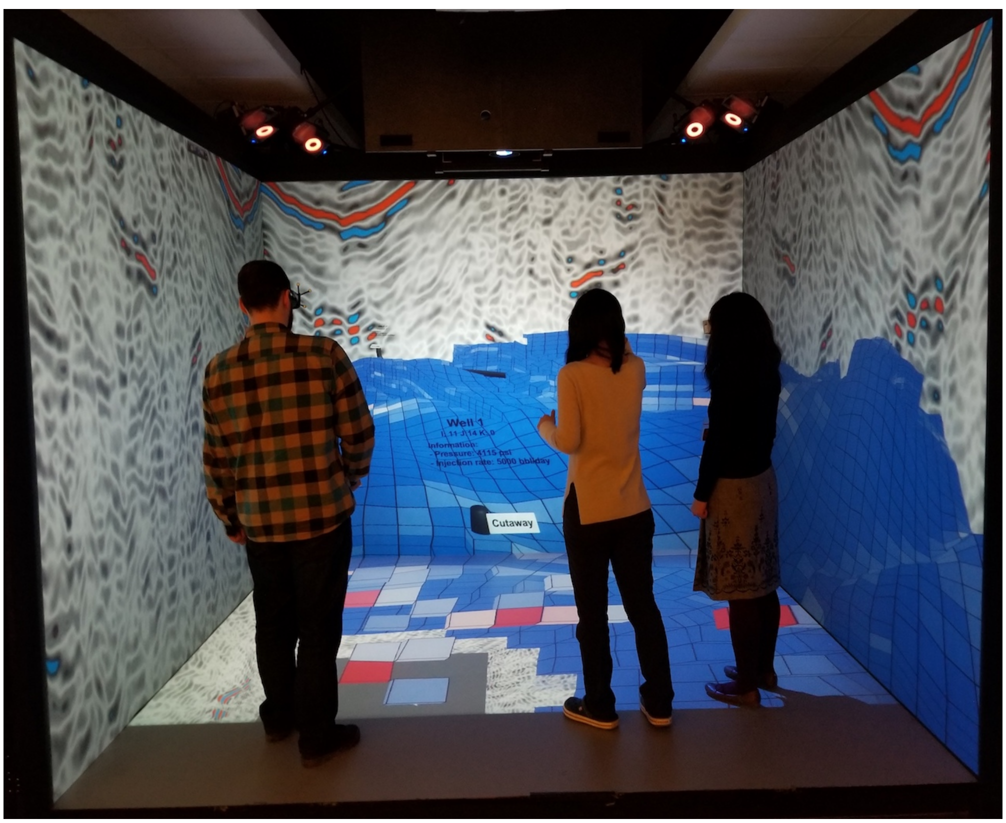

Figure 4.8: Co-located collaboration in the CAVE. This augmented virtuality environment allows for easy user interaction and proprioception but not private views.

4.4 Architecture

The project is implemented using Unity and uses the Unity built in multiplayer tools and services collectively know as Unity Networking (UNet). The tool is set up to have a client-server architecture with one of the instances acting as Host. When rendering the reservoir model, the cell data is loaded from a file. This cell data includes information on the shape of each cell, the location of the cell, and data such as porosity or permeability values for the cell. To render this information a mesh is generated for each chunk of 1000 cells. Each individual cell within the mesh is then coloured based on the data value associated with it. Synchronization of the state of the collaboration session to each each user is accomplished using Unity networking as well. The state of all cells and the position within the dataset are synchronized by distributing changes to internal data structures. Support for simultaneous editing of data is not supported, so only one user is able to edit the data at a given time. The position of avatars, representing each of participants location, also have their position and orientation synchronized. Collaborators can see the location of other users and cues are provided to understand where other collaborators are looking.

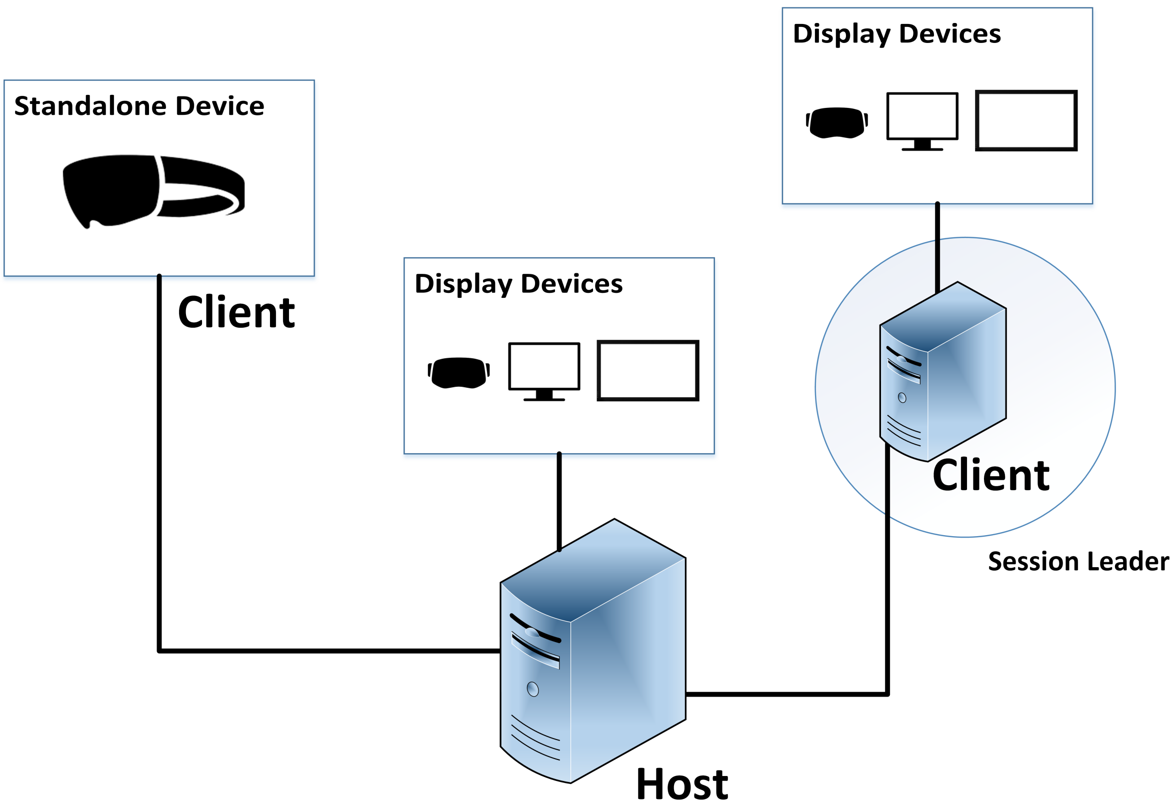

Figure 4.9: Architecture of the immersive prototype. Any system can be a host, and clients can connect to the host. There can be one session leader on either the host or client that can edit the data.

Chapter 5

Collaboration Scenarios

In the previous chapter, an immersive tool for visualizing reservoir data was described. This tool was reported to be an effective means of collaborating over reservoir data by subject matter experts. In order to facilitate collaboration the tool supported multiple platforms. Data can be displayed on conventional screens, virtual reality head mounted displays, augmented reality head mounted displays and a large scale immersive CAVE environment.

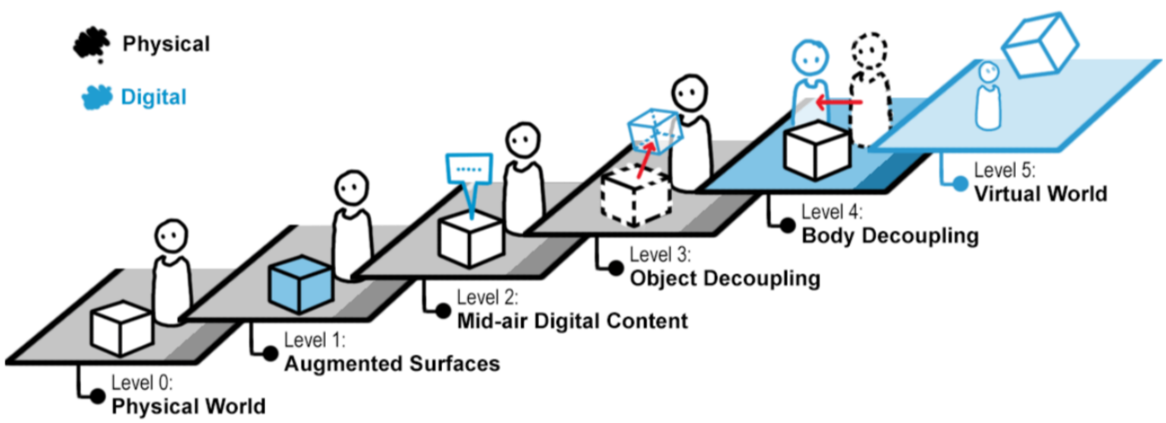

Figure 5.1: An integrated mixed reality ecosystem [258].

The options available for collaboration are increasing and collaboration may involve many different devices, including computer screens, large displays, virtual or augmented reality HMDs, and hand held or spatial augmented reality (SAR) systems [246]. These technologies span the reality-virtuality continuum introduced by Milgram and Kishino with the real world at one end, and a pure virtual environment at the other end. According to Milgram and Kishino, in between the two extremes of reality and pure virtual is "mixed reality", where the real and virtual are mixed. Devices such as the Microsoft Hololens [211] emerged after the reality-virtuality continuum was defined and mix the real and virtual by integrating digital objects into the real world that are trackable and responsive to the real world. This has created another meaning for mixed-reality that refers to this integration of digital and virtual content in an interactive and responsive manner, as opposed to augmented reality that only displays content on top of the real world. When considering collaboration scenarios, another definition for mixed reality may be used, as seen in work by authors such as Benford et al. [28], Salimian et al. [262] and Reilly et al. [250]. These works refer to mixed realities as new forms of shared space that span the dimensions of local, remote, physical and synthetic. Mixed reality collaborative environments connect physical and virtual worlds to present an integrated collaborative space for remote and co-located collaborators.

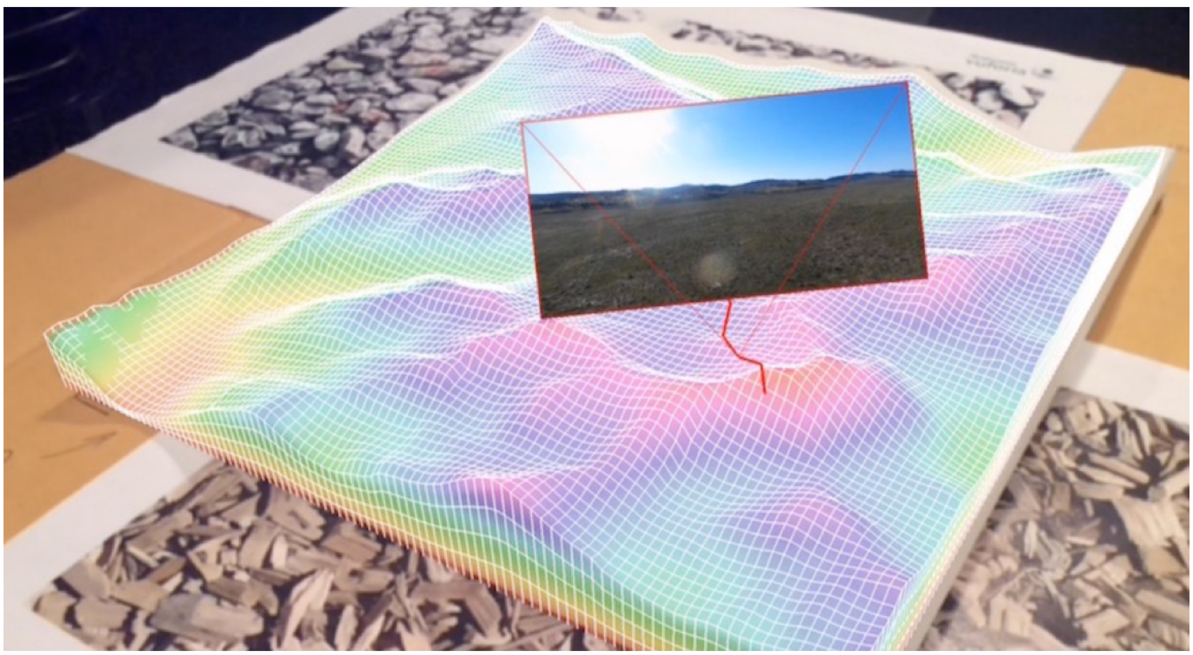

Figure 5.2: Augmented 3D printing from [185].

Various levels of physicality and artificiality may be combined when collaborating. For example digitally augmented 3D printed landscapes have been proposed to deliver a collaborative experience with UAVs [185] and field workers [224]. The entire reality-virtuality continuum can be utilized even within one workflow. Multiple mixed reality modalities have been combined to create an integrated mixed reality ecosystem that allows users to incrementally transition from pure physical to pure virtual experiences. This system stands on a conceptual framework composed of six levels of digital augmentation [258] as shown in Figure 5.1. This allows for users to move it-

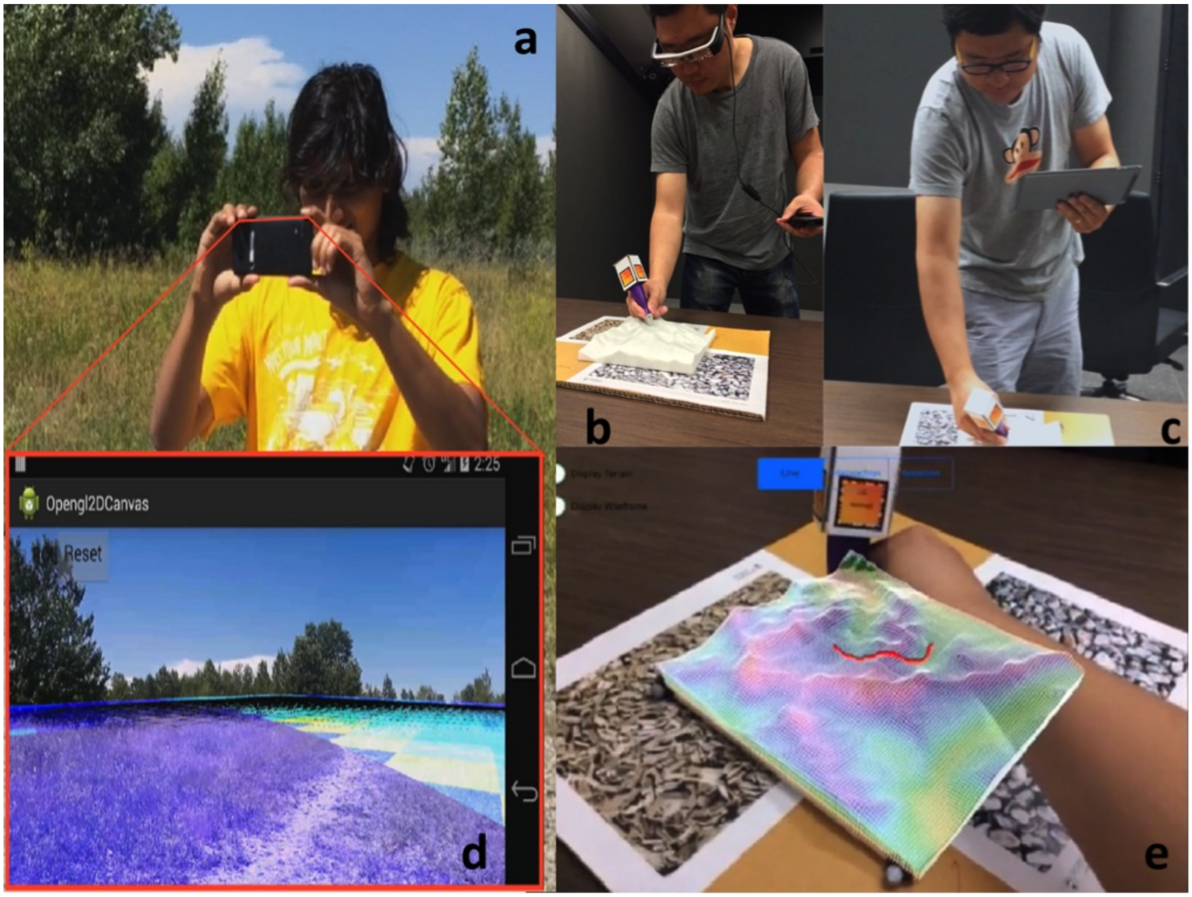

Figure 5.3: Augmented 3D printing from [224].

eratively from physical views to increasingly virtual environments as more conceptual or dynamic information is required, and less in-situ physical context is required. This is illustrative of how varying levels of immersion will likely be used in an increasingly related and connected manner. New techniques are also being introudced that make use of this hardware, such as Holoportation [233], which allows live-streaming of 3D scans of people and objects to immersive devices, allowing them to appear almost as if they are present.

However, there are several issues that need careful consideration when collaborating across heterogeneous devices to provide a secure and usable system. Although many of these considerations are not unique to immersive technologies, the use of immersive technologies by their nature lead to the creation of multiple shared spaces, with a variety of different boundaries and other relationships. Examination of existing works and discussion with users suggests that the integration of a variety of different spaces without clearly identified boundaries between the spaces and clear indications of how information permeates through the boundaries creates confusion about how information or data can flow between spaces. Effects of presence disparity [301] can create confusion about what is being revealed to other collaborators at any given point in time. Collaboration across various scenarios incorporating a variety of technologies and spaces can also result in highly dynamic security contexts. The context can change as new spaces are added, properties of boundaries between spaces change, devices are added, data or information is introduced, sensors are activated, or the composition of identities or roles change across any of the spaces. The location of where processed information, such as visualizations, must be displayed, supporting infrastructure used, amount of control over endpoints and trust in computer networks also influences the security context. However, solutions must also be comprehensible, usable, and allow users to mediate the flow of information or data so that they can collaborate effectively, while maintaining enough control so that the principle of least privilege may be upheld. Mechanisms such as access control policy may be used to help users "do the right thing" in the face of this complexity.

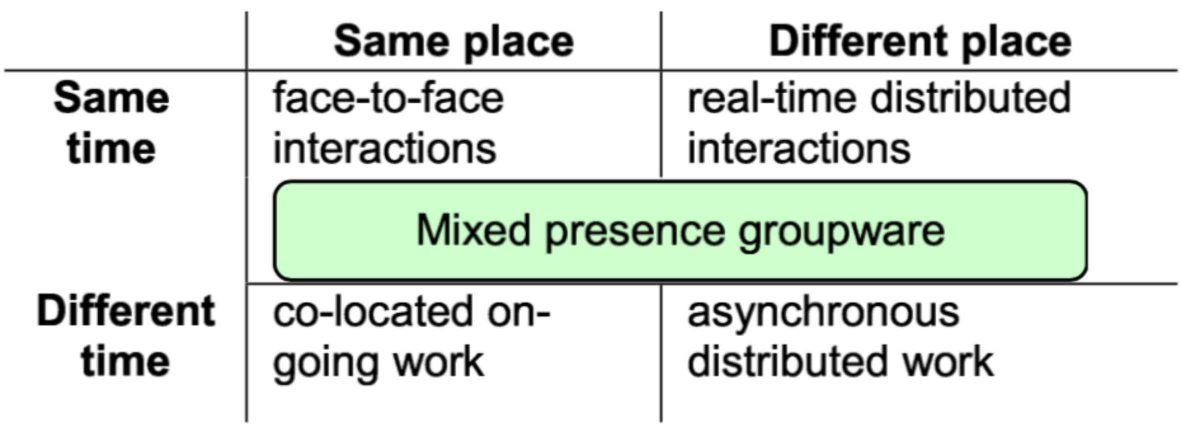

Figure 5.4: Space-time groupware matrix from [301].

Mixed-presence groupware considers co-located and remote participants working together in real-time or asynchronously (Figure 5.4). When exploring the use of mixed-presence groupware, display disparity and presence disparity are identified as an example of one such issue [301]. Display disparity was initially introduced to describe issues related to the orientation of content relative to collaborators when working between screens and tabletop displays. Presence disparity was introduced to describe the issues related to the reduced perception of other collaborators presence when working between co-located and remote collaborators. These issues have not gone away with immersive devices, since working between screens and different immersive devices requires an awareness of both where other collaborators are located as well as how to properly situate data. These issues can disrupt collaboration, and facilitate accidental disclosure of data. Managment of virtual and physical spaces across a variety of devices is has been attempted [77] and many lessons have been learned. This includes the definition of measured space, which represents the awareness of physical space and physical objects in the space that a computer system has due to measurement devices such as sensors. Measured space acts as a form of intermediate space between real space and virtual space. There may be multiple real, measured and virtual spaces involved in a collaboration. Relationships between the spaces are formed by topological, boundary and mapping relationships. In relation to real, virtual and measured space, topological relationships include concepts such as ”contains”, ”overlaps” and ”separate” with relation to shared spaces. The spaces are interconnected by their boundaries and the spatial mapping between them. Benford et al. defined three dimensions to help categorize shared mixed realities linking virtual and real environments [28]. The three dimensions are transportation and artificiality (Figure 5.5) and spatiality (Figure 5.6). Transportation concerns the degree to which users are transported into some new space or remain in their local space. Artificiality concerns the degree to which the shared space is based on real-world information or is synthesized. Spatiality concerns the degree to which the shared space exhibits key spatial properties such as containment, topology, movement, and a shared frame of reference. These definitions can be combined with the Milgram-Kishino reality-virtuality continuum [214] to help define the collaboration environment. Benford et al. were very concerned about the boundaries between shared spaces. There may be multiple boundaries between each shared space, and they may be physical-physical, physical-synthetic and synthetic-synthetic. Boundaries may have a variety of properties [157]. For example, boundaries may be directional with regards to transparency and interaction, meaning they may not have the same level of transparency or interaction between boundaries. A one way mirror into another room is a physical-physical space boundary, but is highly directional. A remotely operated telepresence system may be highly interactive one way but afford no interaction the other direction. The level of awareness of boundaries, the transparency and the directionality are factors that may have in impact on the balance of power, the privacy and the security of data shared within a collaborative system. In addition, multiple, fragmented boundaries may provide a degraded collaboration experience and affords the opportunity for confusion when dealing with sensitive data, risking accidental disclosure of information.

It has been shown that application designers must be careful to ensure that cues suggesting that privacy may be compromised remain consistent with the mental models of the users when mixing physical and virtual collaboration environments, even if not using immersion [262]. These cues may come in a variety of forms. Communication-based cues involve literal communication between collaborators, such as physical gestures or voice communication. Interactive cues can include the spatial location of information being displayed and responses providing feedback for interactions. Ambient cues can include environmental cues, such as audio, indicating where other collaborators are located or where cameras are active. Infrastructure cues include symbols or visible cameras that provide clearly visible indications of how to maintain privacy. If these cues are not clear or present, trust in the application remains low, and data privacy may not be maintained. Effective collaboration suggests fluid movement of dialogue and information between environments and amongst collaborators. However, these design goals are what can predispose users to lose context and clarity regarding what actions ensure privacy across physical and virtual channels. When dealing with sensitive data, it is possible that only collaborative scenarios that reduce presence disparity and allow for cues that users can easily interpret in order to perform actions to protect their data may be suitable.

Another consideration is how to provide space for restricted views of information. When studying tabletop negotiations where users collaborate towards a common goal but also negotiate amongst themselves, Yamaguchi et al noted several important behaviors that must be maintained to support strategic negotiations [331]. Supporting these behaviors required ensuring users have access to private spaces where they can view their data individually, personal spaces where data could be shared with a subset of the group and public spaces where users can disclose information to the everyone in the collaboration. Effective collaboration tools should also uphold privacy and security through notions of territoriality and proxemics, [116], to provide the physical space to work in private [42] [153]. The concept of personal space is also very applicable to virtual environments [327] [196] as the intrusion onto personal space is both uncomfortable and invasive even in a virtual world.

Although an exhaustive exploration of the entire space of possible collaboration scenarios across the reality-virtually continuum is beyond the scope of this work, to explore the design space a few collaboration scenarios will be discussed.

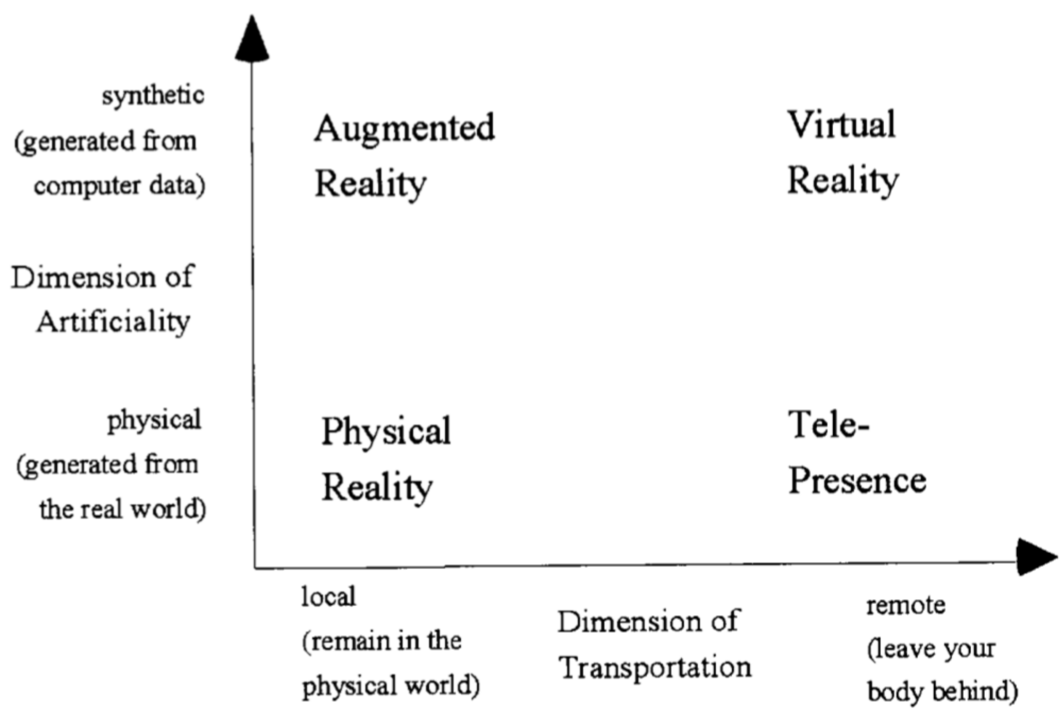

Figure 5.5: Benfords Model: Dimensions of artificiality and transportation [28]. Transportation is the degree to which users and objects are transported to another environment. Artificiality is the degree to which a space is synthetic or based on the real world.

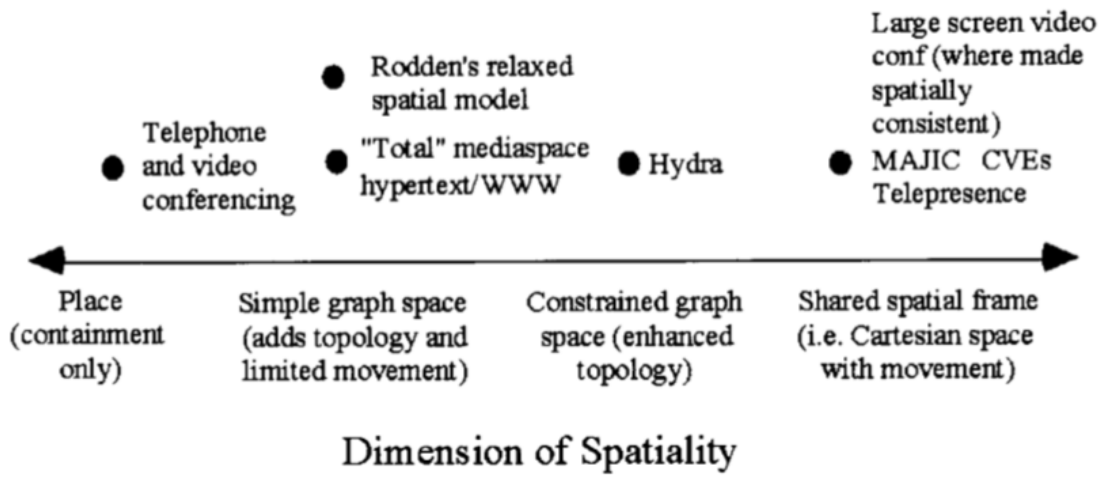

Figure 5.6: Benfords Model: Dimension of spatiality [28].

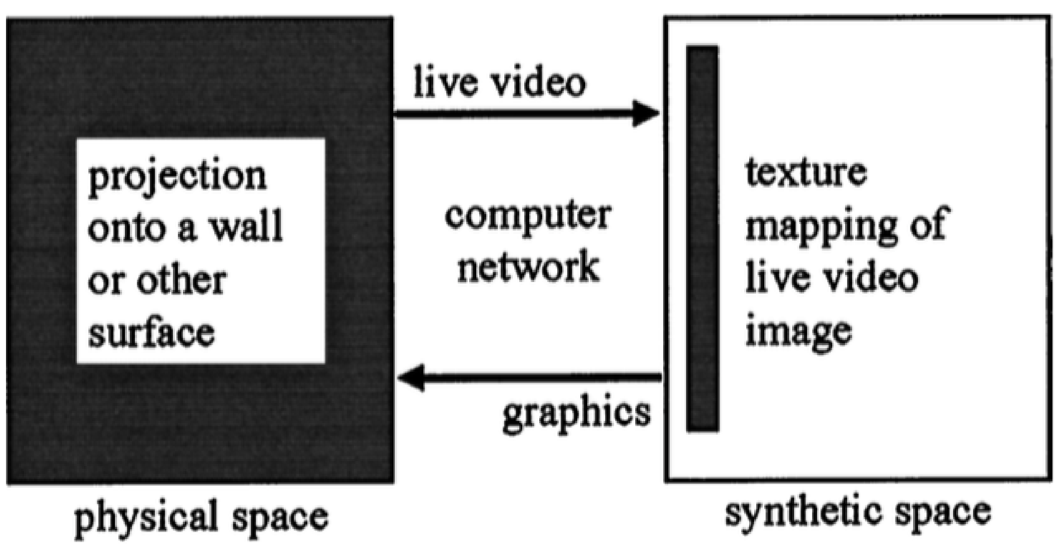

Figure 5.7: A simple mixed-reality boundary from Benford [28].

5.1 Scenarios

5.1.1 Physical Reality Collaboration

In Figure 5.8, users are collaborating together in the same physical space. These spaces could be linked together using technologies such as videoconferencing to create a physical-physical boundary. All collaborators are able to see what ever is displayed in the local, physical collaboration environment.

One important source of inadvertent information disclosure in physical collaboration environments is shoulder surfing. A large amount of investigation into shoulder surfing behaviors, such as the work done by Eiband et al. [84], has shown that it is a non-trival threat. Users may protect their information using methods that they are familiar with, such as adjusting the angle of personal devices, to hide information from view.

Many techniques have been developed to prevent shoulder surfing on public displays. For example, works such as [42] defend against these attacks by detcting gaze and location of surrounding individuals and either warning of potential shoulder surfing attacks or blanking out a screen except where the user is looking. Zhou et al designed a tablet interface that detects when people nearby are looking at the screen, providing awareness through glyph notifications, and response through visual protections [343]. Support for multiple views of information based on different users to support strategic negotiation has been implemented in tabletops [261]. It is important to learn from attacks on traditional platforms and understand how similar attacks can be implemented when using immersive hardware in a variety of scenarios. A complete system to support secure collaboration would ideally incorporate techniques such as these for physical collaboration, in addition to applying them to defend against similar attacks in mixed reality or immersive environments.

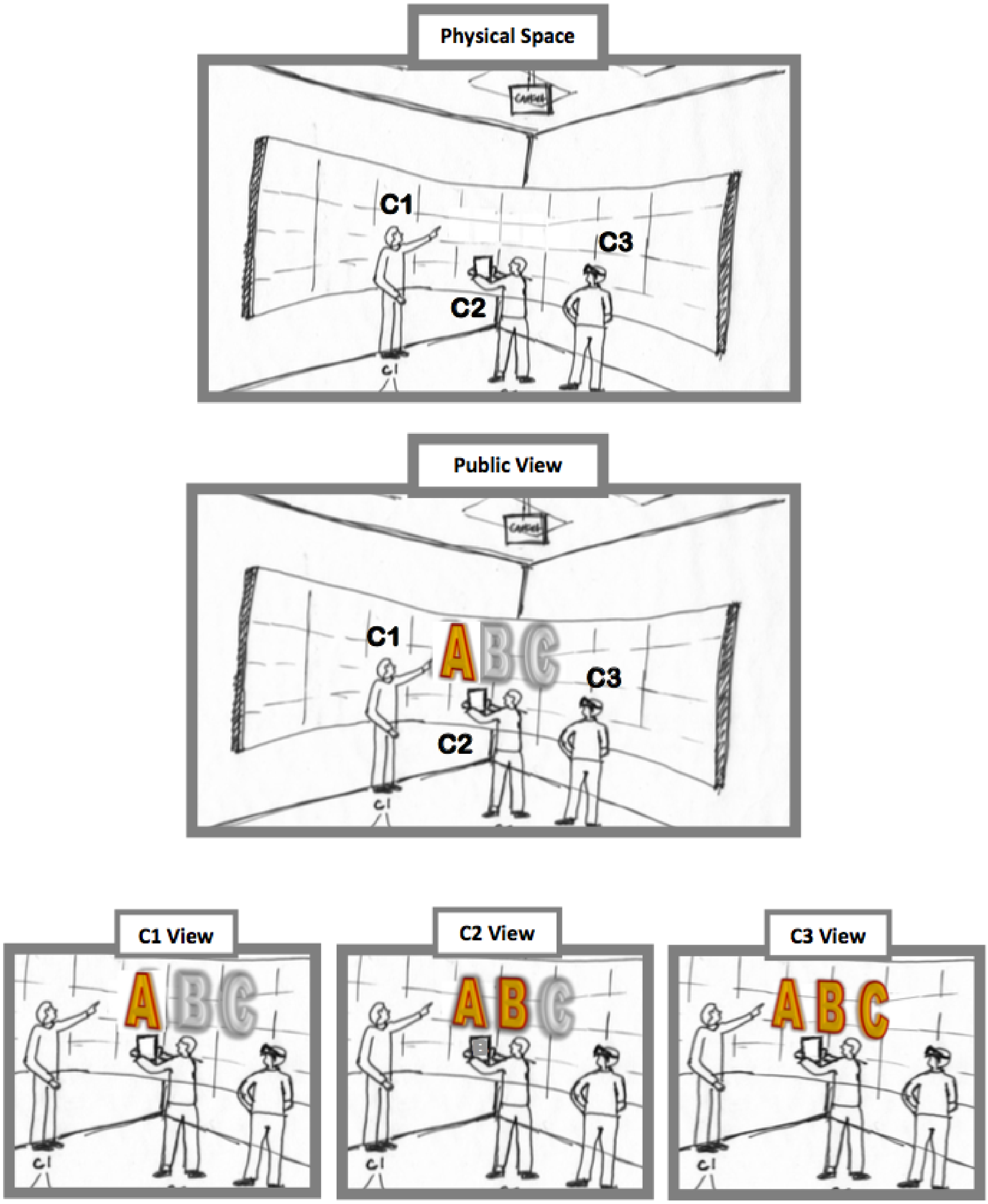

Figure 5.8: Co-located Physical Collaboration.

5.1.2 Virtual Reality Collaboration

In Figure 5.9, users are engaged in virtual reality collaboration. Virtual reality shared spaces may be connected forming artificial-artificial boundaries. In virtual reality collaboration there is opportunity to show information in arbitrary ways, including heads up displays, virtual objects or virtual information surfaces simulating physical screens. Information may be shared on a per-space basis or per user basis. This affords many opportunities to create private, shared and public spaces in which to view data. This freedom presents many avenues for creative sharing, however physical security concerns still exist, particularly if data is shared on a per-space basis. If data is brought into a virtual space from another source it is important to understand how access control policies should be applied to control the flow of information and how territoriality and proxemic zones can be maintained. It is possible that many of the physical security concerns, such as shoulder surfing attacks, still exist and may affect data that is displayed in virtual shared spaces. However, the ways in which information is shared may be less obvious in the virtual world if the application is not designed carefully. It is important to maintain recognizable cues that help users maintain their privacy whenever possible.

Although the shared space is virtual, users are still part of the physical world. It is possible anyone that is not part of the collaboration may observe the virtual reality users in the physical world to glean information. Screens that mirror the headset view, audio communication and movements, such as gestures, may all reveal information to observers without the knowledge of the collaborator in the headset. Although not part of the shared spaces considered for the collaboration tool, designers should still be cognizant that there is always an implicit synthetic-physical boundary that exists between each virtual reality user and their environment.

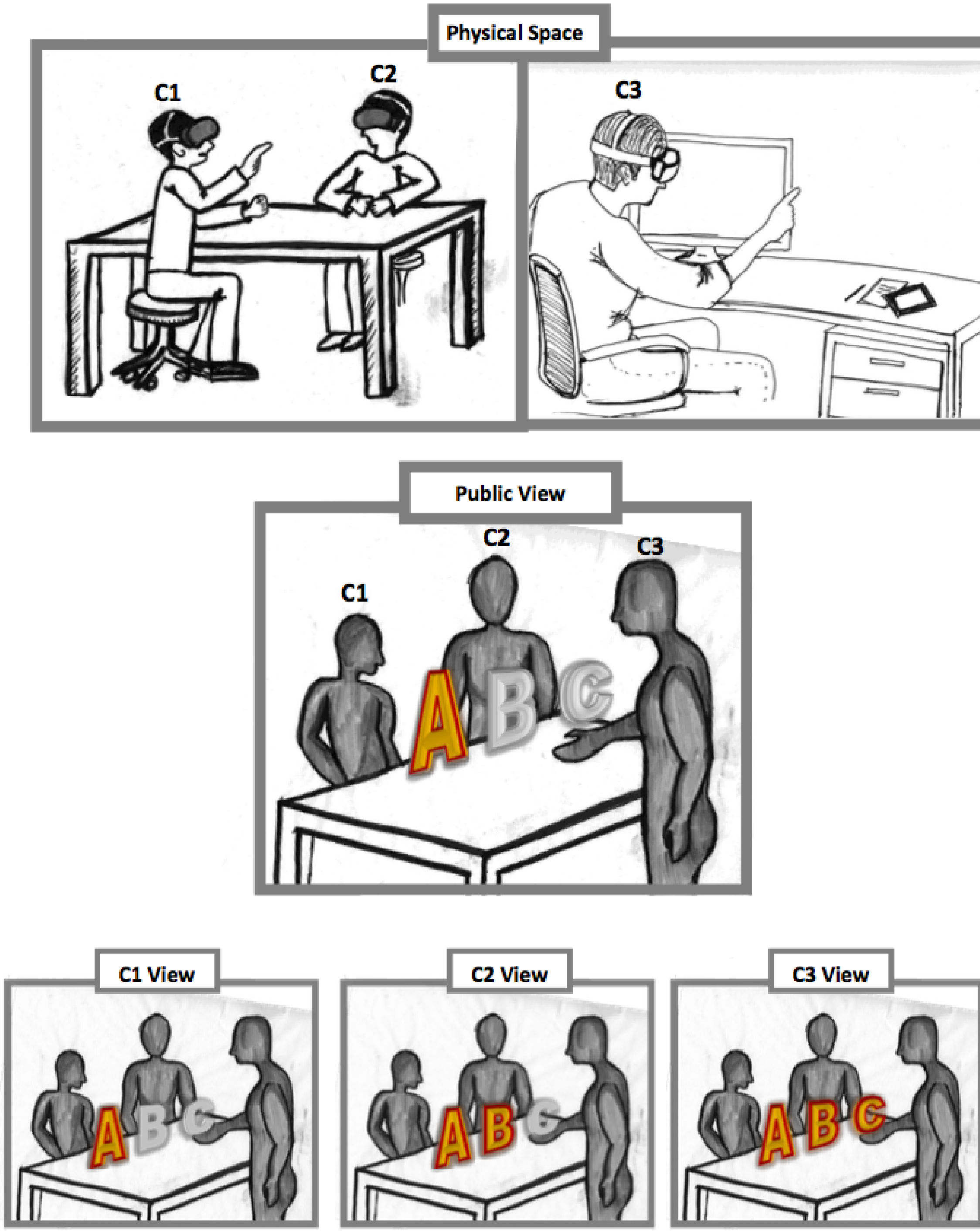

Figure 5.9: Virtual Reality Collaboration.

5.1.3 Augmented Reality Collaboration

In Figure 5.10, users are engaged in augmented reality collaboration. Augmented reality presents a variety of security issues [176]. This includes input security, as a large amount of data is continuously collected to provide an augmented reality experience, as well as output security which is concerned with what is presented to the user in the display. It may be possible for users to see private information on devices or material that is not intended to be part of the collaboration session if controls are not placed on access to the sensor data. For instance, the use of a camera view, which is often used for collaboration applications such as collaborative device repair, may be of concern depending on a variety of factors such as the location of the repair or users participating in the collaboration. Similar to virtual reality collaboration, a variety of means may be used to share information privately to a subgroup of collaborators or to all participants of the collaboration. However, the physical environment must be considered. Information may flow across synthetic-physical boundaries or physical-physical boundaries, and a variety of information flows are possible between these different shared spaces. Care must be provided to ensure flows of information do not lead to accidental disclosure, as users may need to maintain awareness of how to protect information in a virtual shared space and a physical shared space simultaneously. If multiple virtual or physical shared spaces are linked then even more care must be taken, as the way in which information may propagate may be even less clear.

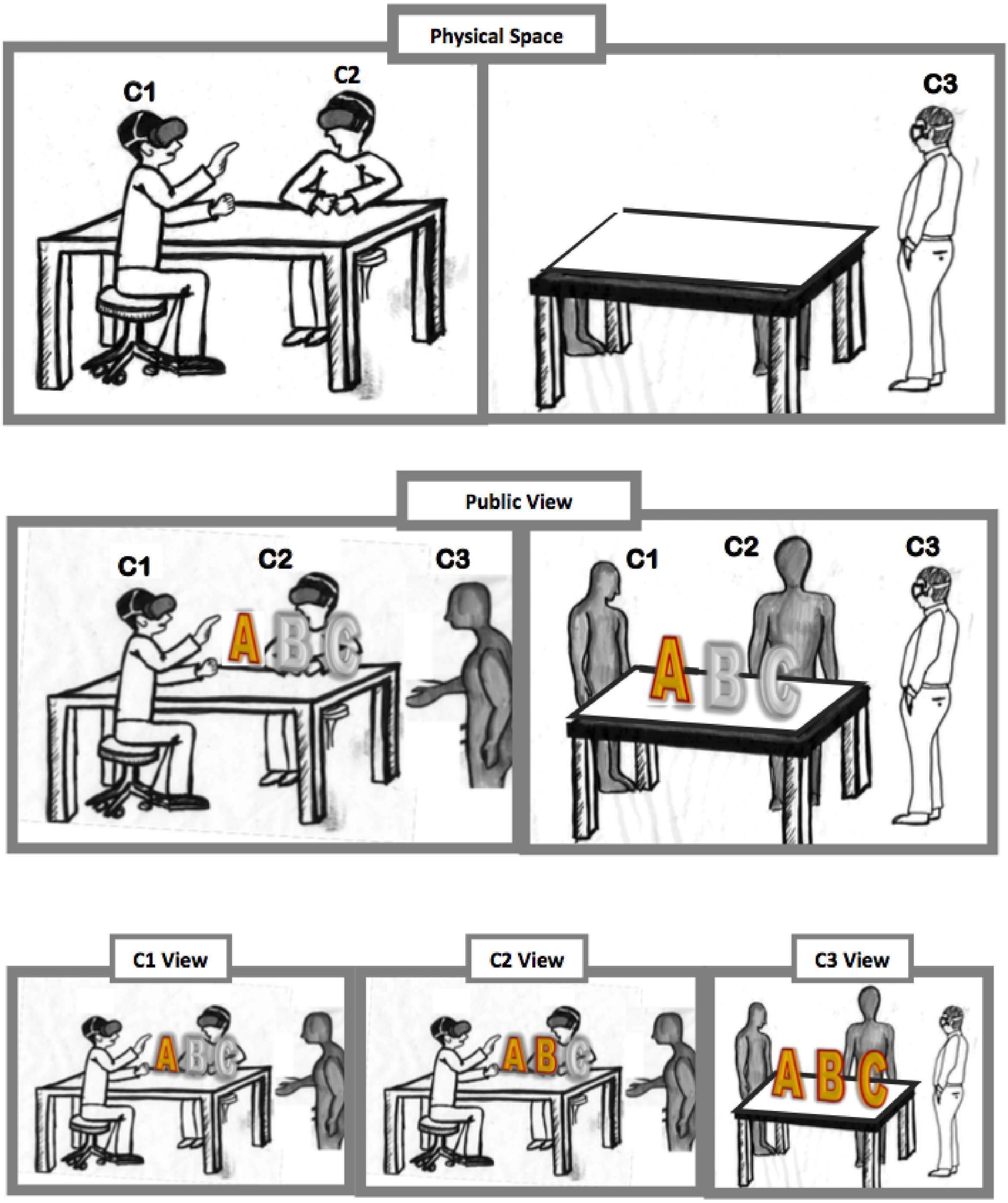

Figure 5.10: Augmented Reality Collaboration.

5.1.4 Mixed Reality Collaboration

In Figure 5.11, users are engaged in a mixed virtual and physical collaboration. A key characteristic of this scenario is the connection of virtual shared space with physical shared space. The spaces may be distinct and adjacent, rather than overlaid. Often a design goal is to have a transparent connection, merging the physical and the virtual in various ways. There is a large amount of potential for the physical and virtual worlds to be very tightly integrated as shown in works such as OneWorld [258] or mirrored as shown in "Dual Reality" by Lifton et al. [191]. Mixed reality collaboration may combine physical collaboration, virtual reality collaboration and augmented reality collaboration, and therefore may have all the considerations of the previous scenarios.

Explorations into environments blending real and virtual environments [262] has shown that many users do not intuitively develop an awareness of how to protect their information when the physical and virtual environments are fused. This can lead to an increase in inadvertent privacy breaches. Display disparity and presence disparity have a large impact on the collaboration experience from both a usability and a security standpoint. When users are simultaneously collaborating in multiple spaces, such as a virtual and physical space, they become confused as to how information may be propagated. This is because it is more complex to manage how information is shared in two spaces. In particular, if cues such as location and gaze are not maintained across the spaces users must be very diligent to keep track of the positions of virtual collaborators and try to infer what they are able to see and guess at what they are looking at. Mixed reality collaboration must consider the increased complexity of information propagation through the physical-synthetic boundaries, in addition to any physical-physical boundaries or synthetic-synthetic boundaries that may exist. As the number of boundaries increases, users must maintain awareness of a possibly changing situation within each space, and understand how information may be propagated through each boundary. Great care must be given to the design of tools supporting mixed reality collaboration if sensitive data is shared, particularly as the number of shared spaces increases or if the boundaries between the spaces have different properties. Mechanisms must be provided to both mediate the flow of information between spaces as well as within collaboration spaces. Visual protection mechanisms that hide or obfuscate data or information can help mediate information between collaborators within a collaboration space. Access control policy and manipulation of boundary properties or visual protections applied to views across boundaries may provide security and privacy assurances between spaces.

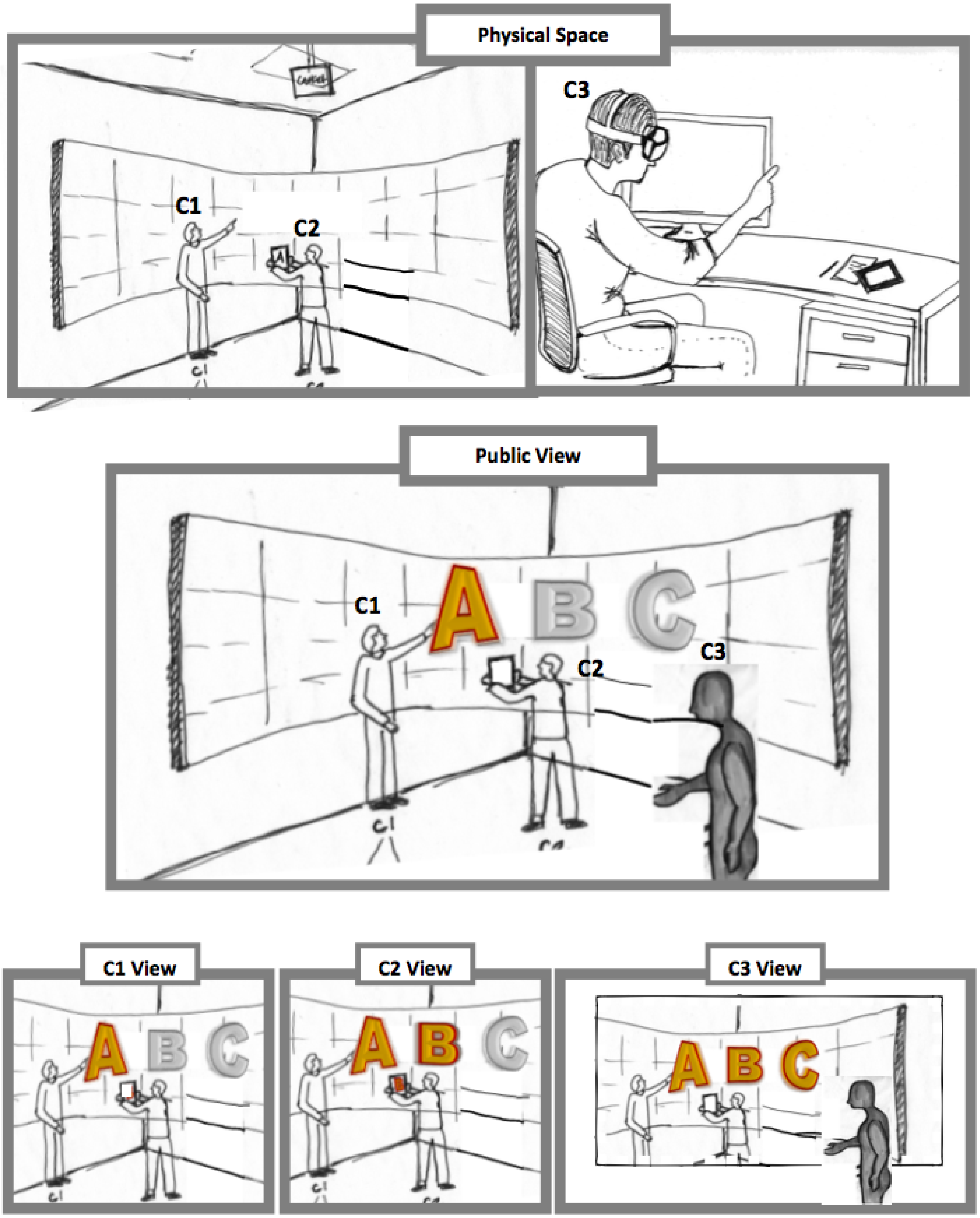

Figure 5.11: Remote Mixed Reality Collaboration.

Chapter 6

Protection Mechanisms

There is a large body of work looking at collaboration using a variety of technologies including conventional devices, wearables, and immersive hardware. There is also a large body of work exploring the various security components that might be used to secure these technologies. However, it has long been demonstated that without designing for usability, attempts to design secure systems and software will in fact make them less secure [326] [5]. The hope of this work is to explore enough of the design space to build a prototype incorporating a small subset of the available options in order to gain feedback from subject matter experts. With this feedback, the inital design may be validated or alternate designs proposed. This will provide direction for the longer-term goal of providing a tool that supports the usability requirements and security needs of professionals that must collaborate over sensitive data. Due to the increase in complexity when incorporating and combining new technologies, it is important to carefully design the applications for the workplace, ideally considering the social, application and infrastucture context of how the technology will be used [186]. This includes performing traditional security requirements engineering [263], while also considering the unique challenges of securing wearable devices such as augmented reality [277], and collaborative environments [128]. Some key design questions that are universal [284] must be considered in light of the the secure collaboration tool:

1. What access control policies are suitable to provide authorization decisions across technologies and across scenarios?
2. What access control methods are suitable to protect the information while providing effective collaboration?

Rather than focusing on finding the perfect mix of technologies, the intention is to follow a more human-centred design approach. Agile frameworks such as Scrum [267] have had enormous success since they allow for iterative development as requirements are elucidated, allowing for shorter hypothesis validation cycles. Attempts to integrate security requirements engineering and design into agile methodologies [205] [24] [253] are a logical application of these techniques. As noted by Sven Turpe, ”To succeed, security requirements engineering needs to iterate through the components of security needs and analyze their mutual influences until models converge” [314]. He advocates focusing on a broader view of security requirements engineering that is based on an examination of threats, security goals and system design.

For this reason, some possible solutions that may be incorporated into the tool will be explored. This discussion will provide the foundation for selecting solutions and forming hypotheses regarding the design choices. Development has started by implementing a minimum viable prototype to test ideas around a usable security approach based on user needs. Based on feedback from the prototype, insight into the requirements will emerge, which will drive the final selection of the specific security architecture components.

6.1 Access Control Logic

In the interests of developing a minimum viable prototype to iteratively perform requirements engineering, a simple system with basic access control policy was implemented. As more functionality is built, there will be greater clarity into the attributes required to support the functionality required.

In the prototype, four sensitivity levels can be assigned to the classification of objects such as regions of data:

H	Restricted (most sensitive)
M	Confidential
L	Internal
P	Public

Table 6.1: Data sensitivity levels (object attributes). These are sensitivity levels used in at least one oil and gas company.

Users have an attribute attached to them that defines their access to the sensitivity levels. In this system it is configured similarly to a mandatory access control system, since users are effectively assigned a pre-determined clearance level. This level determines the access to the data they have. A user may see data lower than their clearance level, but they may not see any data higher than their clearance level. The prototype not only allows binary, all or nothing, access to the data. Users may be denied access and provided full access. Users may also have a third level of access that provides only a lower fidelity view of the data. This provides a conceptual overview of the information while reducing the detail available. This is very helpful for collaboration since a user with a higher level of access can collaborate with users with lower levels of access, when a conceptual view of the information will suffice.

The system can be set up in two ways. The first way is discretionary. A user with a given clearance level can grant conceptual access to forward a discussion and build understanding. Although this may present some risk of information leakage, there is also the opportunity to forward collaboration effectively while allowing users greater control over the flow of their information. Allowing the user to provide conceptual access, at their discretion, can provide the opportunity to move collaboration forward while providing a minimum of unwanted information dissemination. This only works if the conceptual view is carefully crafted to provide enough information to be useful for the collaboration goals, but not so much information that users have too much understanding of the data. This is admittedly a fine balance that may be highly context dependent.

The system may also be a fully Mandatory Access Control system. This is what was configured for the evaluation. This system is achieved through the use of additional modifiers that provide finer granularity with regards to what the user can see. In this system users also have access level attributes. All users will have conceptual access to data at their level without an access modifier. In this prototype the only access modifier is the detail modifier (D). Users with this attribute are able to see a detailed view of the data such as cell property values with a matching sensitivity level or lower. A user with only a conceptual view will be able to see the detail view of any levels lower than their current access level. While a conceptual view could have a different meaning depending on the application, the core intent is to emphasize conceptual details important to the collaboration, while removing details may reveal sensitive information.

A simple (constructed) example is a virtual reality collaboration of a new spaceship. Perhaps the collaboration contains some equipment that is classified at a sensitivity level higher than one of the collaborators. Rather than hindering collaboration by not allowing the person with lower security access into the collaboration, a conceptual view showing a generic piece of equipment or conceptual information such as a sketched outline of the equipment could be shown to the user. This would allow collaboration since the tour of the spaceship could still happen, yet the need to protect sensitive equipment would be upheld. Users with access to the information could still reveal select details about the equipment to the lower privilege user as needed through verbal communication. Users with access, the “data owners”, are able to mediate the flow of information according to their preferences and the needs of the collaboration.

A similar situation could occur in an oil and gas reservoir scenario. However, instead of classified equipment, sensitive regions may be protected by removing the ability to see any property values. This can be accomplished by disabling the property colour ramp in the sensitive region of the visualization and disabling interactions to probe for property values in the region. A user with this conceptual view, would still be able to see the structure of the region, such as faults and well locations. The users with full access would be able to mediate the flow of information, by disclosing information according to their preference and the needs of the collaboration. If a region is too sensitive to even show the structure of the region, then all information can be hidden by using a completely opaque visual protection mechanism that hides both the contextual and detailed information.

The context attributes allow the application to be aware of the scenarios described. This allows the application to activate protections specific to each scenario. For instance, in the mixed reality collaboration, additional protections can be provided to prevent accidental disclosure of informa-

H	D	Restricted with detail modifier
H		Restricted
M	D	Confidential with detail modifier
M		Confidential
L	D	Internal with detail modifier
L		Internal
P		Public

Table 6.2: User access levels (subject attributes).

VR	Virtual reality collaboration
AR	Augmented reality collaboration
MR	Mixed reality collaboration

Table 6.3: Immersive collaboration scenario (environmental attributes).

tion due to user confusion about the mixed environment. Augmented reality devices could use context to decide if access to the camera should be permitted if there is is sensitive information in the location where the collaboration is occurring. Virtual reality devices could show privileged information only if there is not an additional view into the VR collaboration that could show information to unauthorized individuals, such as an additional monitor that is commonly used to display what a user is seeing.

Attributes may be used to enforce a variety of behaviors depending on the security need and even other considerations such as performance. For example these techniques are applicable to controlling if data is rendered on the client or on the server as discussed in Appendix B.

6.2 Access Control Methods

When users are working on reservoir data in the tool, a protection box may be created that assigns a security classification level to a region of the data set. For instance a user can create a box around a well head with classification ”confidential”. Then, according to the access attribute of other users, they have different views of the data within that box. If a user has no access, they see a completely opaque box that shows no information. If they have full access, they see an outline so that they can see there is a protection box on the region, however they would see a full view of the information and be able to probe and add and remove cells. If a user has only conceptual access (no detail access modifier), then they would see a a box that removes the color of the cells so that the cell property values in that region are not able to be understood. Also, a user with only conceptual access can only see the view from outside the box, they can not go into the box or edit or probe cells to see cell information. This allows them to understand the form and spatial location of the data but not the details. Users can meaningfully collaborate with one another, while still providing some protections for their data. Users with no access attributes are considered to have public access level and are not able to see any data (conceptual or detailed view) in any protection box. They would only see an opaque box.

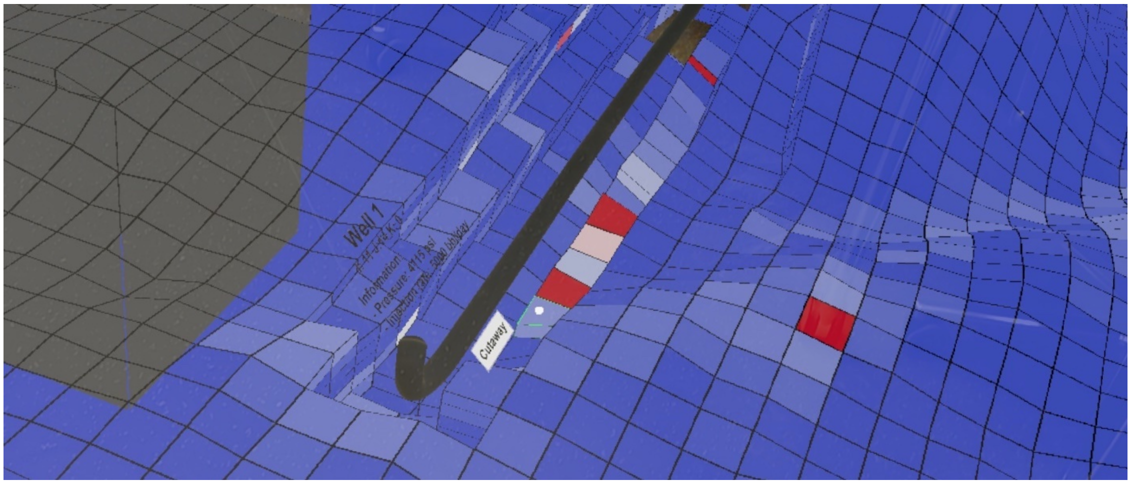

Figure 6.1: Reservoir scenario view of wellhead on Hololens with cells cut away around the well for inspection of interior cells.

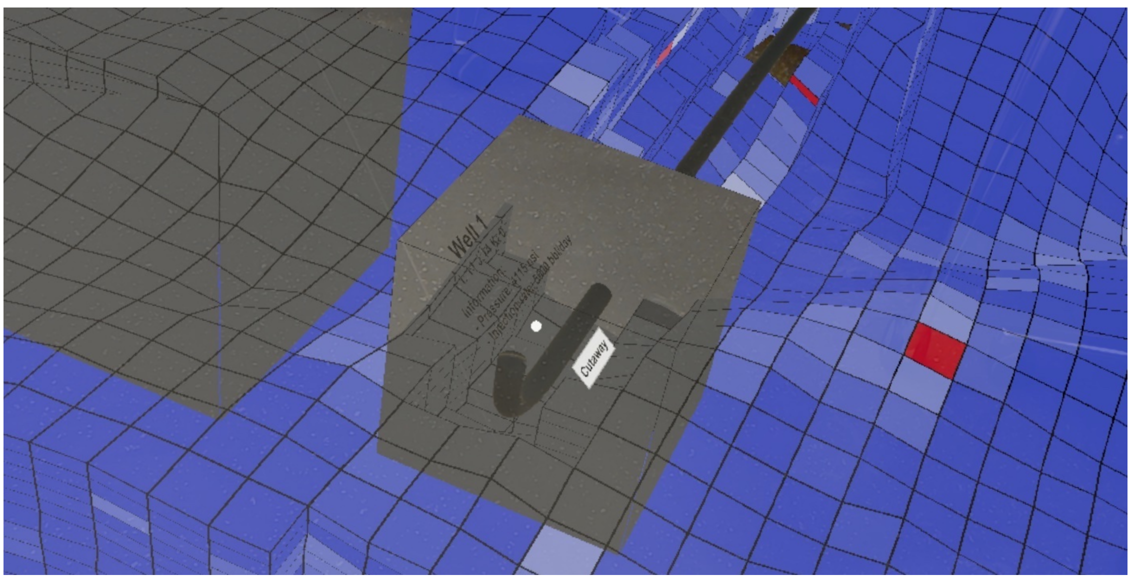

Figure 6.2: Reservoir scenario view of wellhead on Hololens with conceptual protection box removing understanding of cell properties. Cells also may not be probed for values.

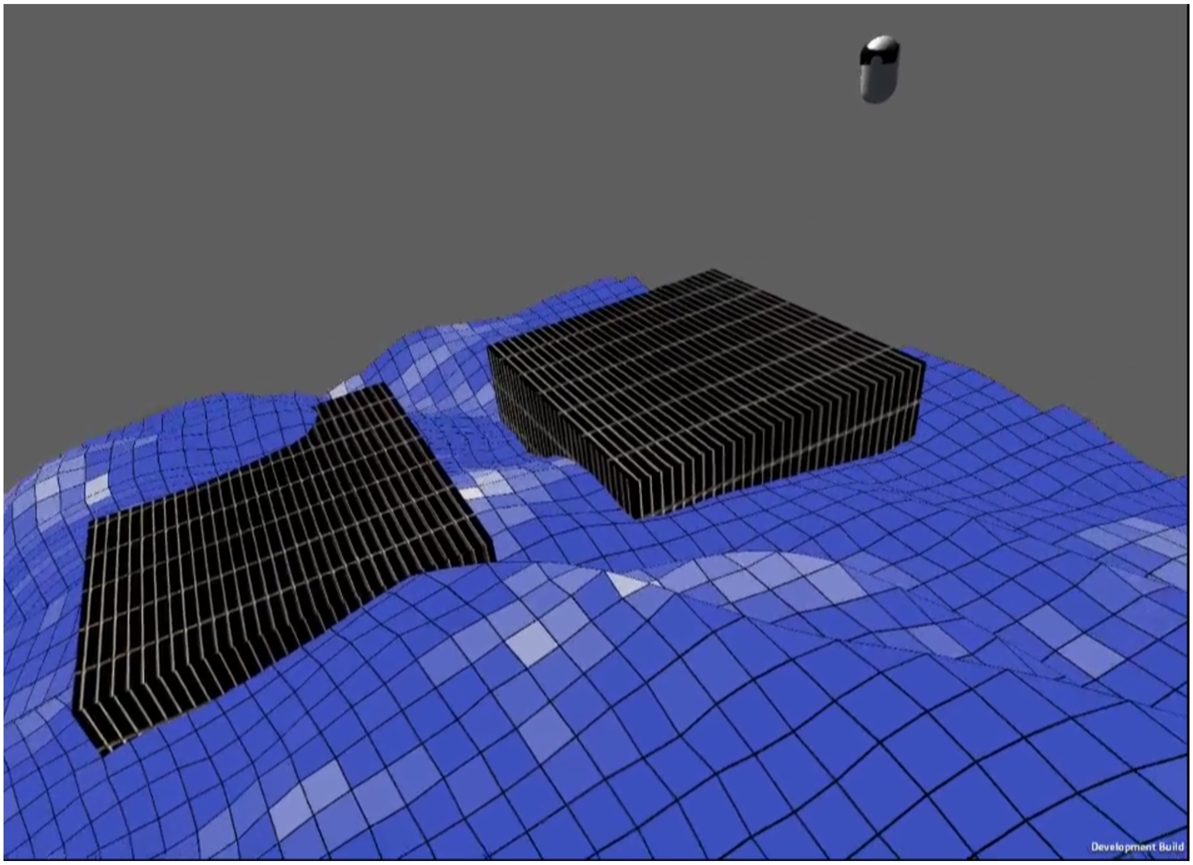

Figure 6.3: Two protection boxes where the viewer has no access on the Oculus Rift.

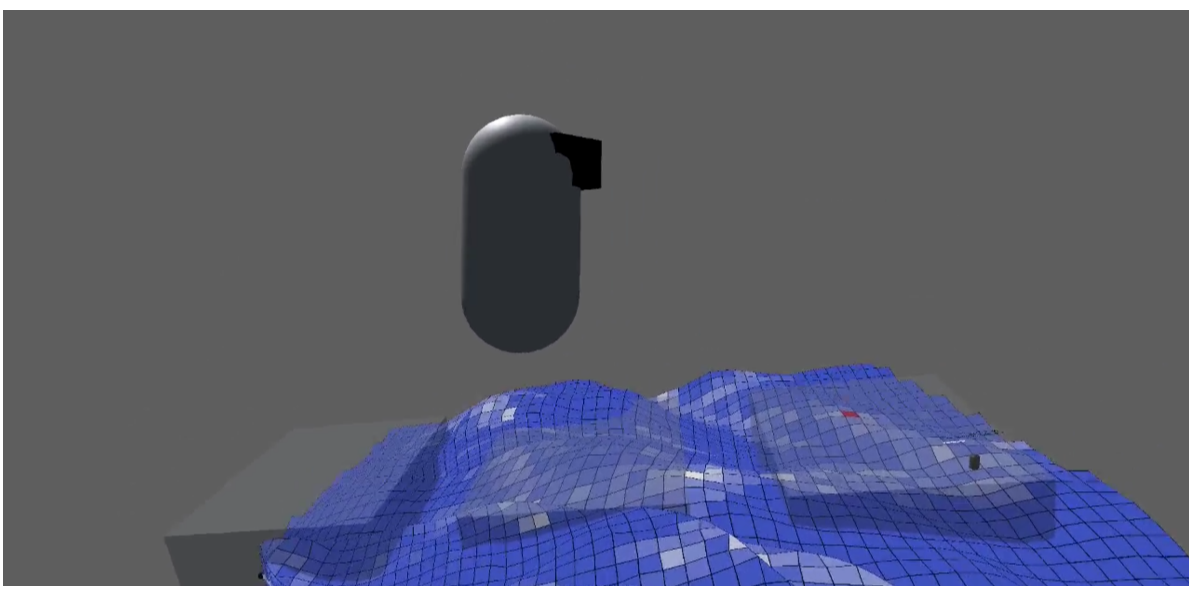

Figure 6.4: Transparent protection boxes where the viewer has access on the HTC Vive with another users avatar in the foreground.

Chapter 7

Feedback Session

A collaborative, immersive prototype tool for viewing static reservoir data and assessing well placement has been implemented and described. The immersive tool has been tried by a variety of oil and gas industry professionals to determine if the tool is usable and useful for their work. This included verifying if the use of immersion provides benefit, if the interactions and features are helpful for reservoir engineering workflows and if the tool can promote the mental state of flow when used. Encouraged by the positive feedback received regarding the immersive tool, attention was then focused towards enabling collaboration over sensitive data. Several collaboration scenarios have been discussed, and basic access controls and visual protection mechanisms have been implemented to support secure collaboration over sensitive data using the immersive tool.

Throughout this process, students and professionals in reservoir engineering have been consulted to guide the design of this proof of concept. However, formal feedback sessions are required in order to gather evidence the tool does address the needs articulated during initial design consultations, and that the application of visual protection and access control mechanisms as implemented in this tool do provide value to professionals in the oil and gas industry. The feedback sessions also acted as a forum for discussion, allowing themes to emerge and potential improvements to be documented. For these feedback session, one collaboration scenario was selected, and a task representative of a common reservoir engineering workflow was used with the visual protection mechanisms. In order to explore the confusion when working in multiple spaces, especially between physical and virtual spaces, a simple test was integrated into the feedback sessions to determine if reservoir engineering subject matter experts would intuitively understand how to protect information when working in such a scenario.

7.1 Scenario

The selected scenario is a mixed reality collaboration scenario. In this scenario, two users are collaborating in a virtual world using VR head mounted displays. An augmented reality collaborator can collaborate with another user in the same physical location providing co-located collaboration. All users are participating in the collaboration session together in the same room for convenience, however, the virtual collaborators in VR headsets could be remote collaborators with no effect on the scenario used for this evaluation.

This provides an excellent environment to test the proposed security mechanisms, since the more complex scenario may reveal more information regarding the strengths and weaknesses of the design. Further to this, mixed reality collaboration scenarios are subject to their own specific security considerations. Explorations of environments combining virtual and physical collaboration such as [250] and [262] have shown that due to a lack of experience with mixed reality collaborative environments users do not always have an awareness of the cues or the mental model required to understand how to protect their information. The scenario in the exploration by Saliman et al. does not involve immersive technology and is focused around a different configuration where users are collaborating around a physical table that is linked to a virtual environment using cameras. However, there are parallels between these scenarios and the one used in this study. In both cases there are mixed environments, where users are focusing on a task and likely do not have well formed mental models regarding the dissemination of data across the virtual environment and the physical environment. Without familiar cues that they can use to guide behaviours users may accidentally reveal information. The mixed reality scenario used to evaluate the security mechanisms provides an opportunity to explore some of these considerations during the feedback session.

7.2 Hypothesis

There are two hypotheses to be validated through the design feedback session. The first is to validate that the protection mechanisms are supporting the design goal of allowing effective collaboration while providing the ability for a user to maintain the principle of least privilege and maintain control over their data. The second hypothesis is to see if the security risks reported in other mixed reality collaborative environments are applicable to the one in this session involving immersive collaboration.

1. The tool allows users to collaborate over a reservoir engineering data to achieve a representative task while maintaining control over the dissemination of their data.

2. Users suffer from the same confusion and lack of clarity regarding how actions affect privacy in a mixed reality scenario as seen in [262].

7.3 Methodology

Prior to the study there was a screening and orientation session that included a simulation sickness quiz to determine suitability as a participant. The quiz used to determine risk of simulator sickness was based on the Simulator Sickness Questionnaire by Kennedy et al. [148]. If the quiz indicated a participant was susceptible to simulator sickness, they were be advised to not participate in the study.

First participants were given a one-on-one guided introduction and orientation to the immersive technology and the application. This was a one-on-one session. Users were provided a introduction to the immersive technologies (VR and AR headsets). Users tried all the immersive devices used in the session including the ones they were not using themselves. They were allowed to try them until they were completely comfortable using the devices. They were also provided the opportunity to use the tool and its interactions. Through this procedure, any observation or feedback reflects the experiences and actions of users that are competent and comfortable using the immersive devices and application.

7.3.1 Assessment of Secure Collaboration Tool

When considering a reservoir model, there can often be individuals that have different affiliations or access levels working in the same region. In order to reflect this, the three participants involved in the collaboration task were assigned different access levels.

U_H was given the role of the data owner and was allowed full access (restricted access) to the dataset and all information in the model. U_H was given the HTC Vive virtual reality device.

U_M was given the role of a collaborator, such as a contractor or potential business partner, and was allowed allowed only conceptual access to confidential data (and full access to internal data). U_M played the role of an expert in well placement acting as an advisor to the data owner. For this reason U_M is not allowed to see the scenario in full detail, but still must guide user U_H and together they must collaborate over the data around the well head. U_M was given the Microsoft Hololens augmented reality device.

U_L was given the role of an intern or trainee observing the well placement decision only. This participant was allowed access to public data (no access to restricted, confidential or internal data). U_L was collaborating using the Oculus Rift. Since this feedback session had all users in the same room, audio channels were unprotected. This does mean that technically some higher level information could be leaked to U_L during the discussion. However, the intent is to validate the visual protection methods, and in this particular scenario any potential leakage over the audio channel has no bearing.

U_H	Restricted access (High) plus detail modifier D
U_M	Confidential access (Medium) with no modifier
U_L	Internal access (Low) with no modifier

Table 7.1: Users in collaboration and their access attributes.

Three protection boxes were pre-created prior to the feedback session. One box, with a sensitivity attribute of confidential (M) was placed around the wellhead, where U_H and U_M were collaborating.

Another box with a sensitivity attribute of restricted (H) was placed around the middle portion of the well. If a competitor were able understand the full detail around the middle of the well, then critical information about the production and viability of the well could be inferred.

The last part of the well was protected with a protection box, but only with the label internal (L), the lowest level of sensitivity.

U_M would see a box surrounding the well head region. This box was translucent but would not allow the colour of the grid cells to be visible. This means that U_M could see the structure and spatial location of the well in the geological data, but not specific cells or spatial distribution of properties.

Protection Box	**Location**	**Label**
B_M	Wellhead	confidential (M)
B_H	Middle	restricted (H)
B_L	Tail	internal (L)

Table 7.2: Protection boxes along well path.

Next, the users were asked to perform a simple task that is representative of reservoir engineering work. A common task in reservoir engineering is to analyse if an oil well is in the correct location based on geological properties. This is determined by considering the property values of the cells around the well, and the context of the geology in the surrounding region. The three participants were assigned a task where they were asked to collaborate over a horizontal well embedded in reservoir data and come to a consensus regarding the location of the well in the geological data. If the well was placed in a reasonable location then the well placement was considered ”good” (the well should stay in the location) otherwise it was considered ”bad” (the well should not stay in the location). One of the key property values is porosity, and in the model the property displayed was porosity along a red-blue colour gradient. Brighter reds indicate a high porosity value and darker blues indicate the lowest porosity values. This allows users of the application to see the porosity and therefore the suitability of the geology for well placement at a glance. Quantitative porosity and permeability obtained by probing cells is also used in decision making.

The participants were instructed to assess the quality of the well placement by checking if there are a number of cells with a specific color in the region of the well. U_M with lower privilege would ask U_H to find cells with a certain colour within a distance from the well head set by U_M. U_H then checked and reported if the well placement meets the required criteria. U_L was allowed to ask questions and told to observe the collaboration carefully.

After the task, users were asked to complete a series of post-task questions and interviewed using a semi-structured interview. In particular each of the participants (the subject matter experts) were asked if they felt like the collaboration was effective and the data owner was asked if they felt their data was protected.

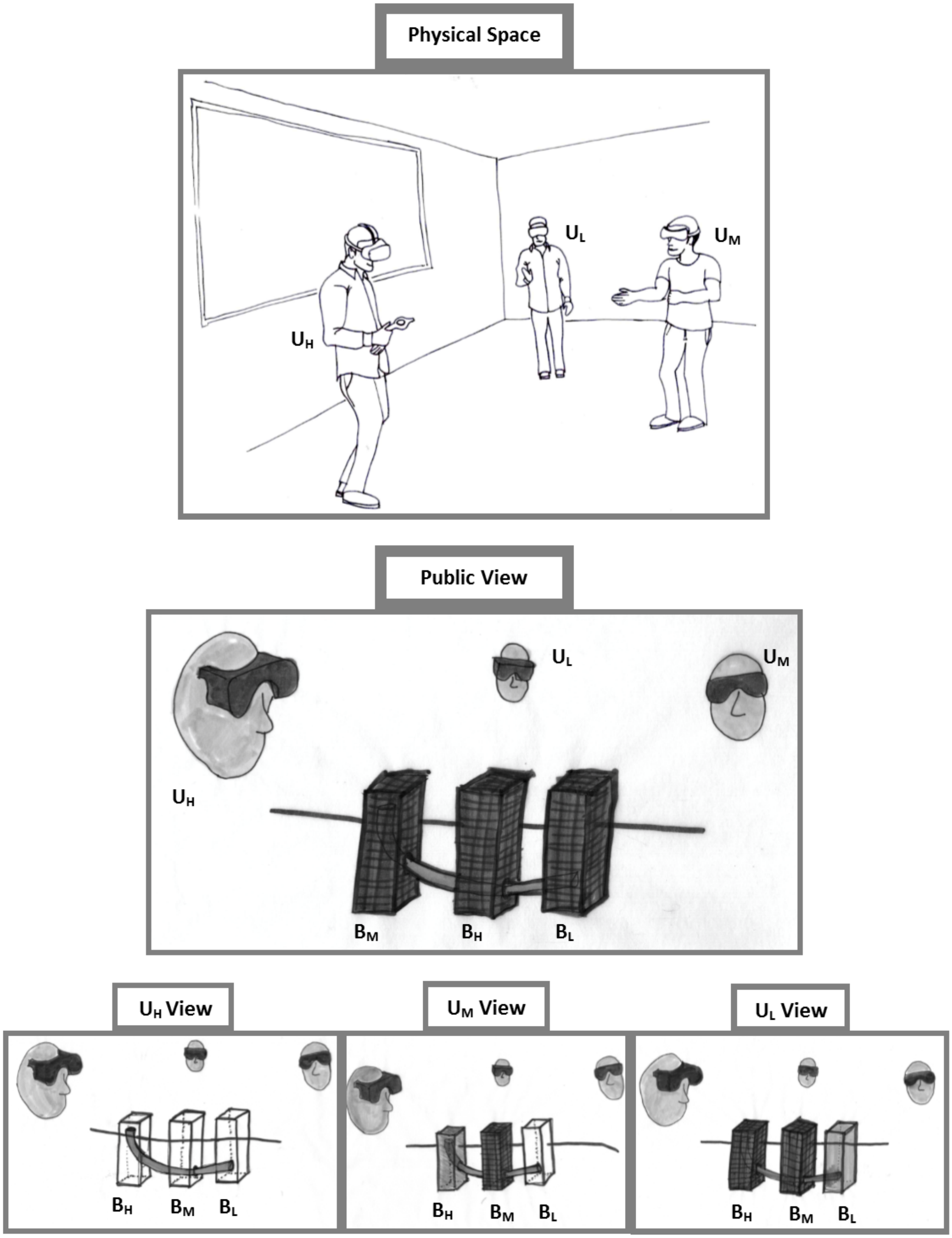

Figure 7.1: Concept drawing of evaluation scenario with physical space, public view (no access level) and perspective of each user.

7.3.2 Mixed Reality Collaboration Test

After consensus was reached regarding the well placement, a pretend ”manager” entered the room to ask the user with restricted access U_H if they could display their view to the public screen in the room where the collaboration was being done. This was a test to confirm the suspected confusion around interactions between virtual and real worlds. If U_H were to release their restricted view of the screen it to the public display, it would indicate they have forgotten that there is an augmented reality user in the room that can see this view through their transparent device.

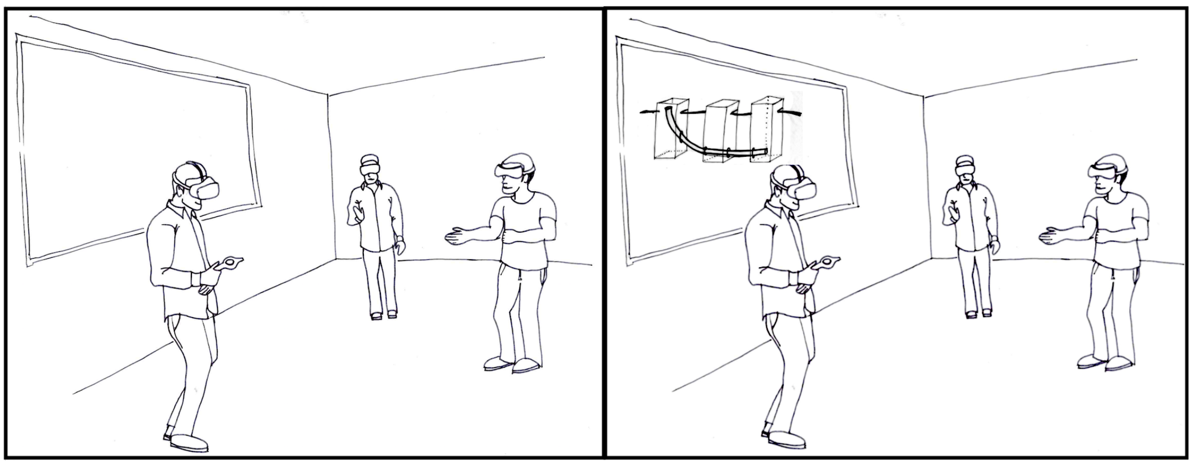

Figure 7.2: Test to determine if U_H would inadvertently reveal privileged view to AR user.

7.4 Users

Two feedback sessions involving three participants each were performed. They consisted of petroleum engineering subject matter experts between the ages of 25 and 41. All had undergraduate degrees in petroleum engineering and were current petroleum engineering graduate students focused on reservoir engineering or researchers working in petroleum engineering research. One had four years of professional experience as a reservoir engineer, and one had one year of professional experience as a reservoir engineer. All participants had been trained on the tool, and provided time to use and explore all the different devices so that they were familiar with the tool and all the immersive devices.

7.5 Results

Although the results are preliminary, the feedback was encouraging of this solution, while also providing some valuable areas for further improvement. It was expected that the feedback would be positive, since informal meetings and discussion with other subject matter experts were used to inform the design of the tool and the protection mechanisms.

Figure 7.3: Feedback session 1 with reservoir engineering subject matter experts using HTC Vive, Oculus Rift, Microsoft HoloLens and a public display.

Figure 7.4: Feedback session 2 with reservoir engineering subject matter experts using HTC Vive, Oculus Rift, Microsoft HoloLens and a public display.

7.5.1 Assessment of Secure Collaboration Tool

All participants verified that the scenario that reflected the work that is typically required of reservoir engineers. They reported that work such as this is currently typically done either by privately consulting a reservoir model off-line from a collaboration session, or manually sanitizing datasets and collaborating over them on a screen. These traditional methods of collaboration can be time consuming and possibly more error prone. All participants reported that collaborating over reservoir models with sensitive data was both needed and a process that is not easy or fast with existing methods. They reported that the conceptual view was an excellent way to protect information while providing sufficient context to collaborate effectively. All users also felt that the balance of information sharing was appropriate in that the data owner was able to adequately protect their sensitive region and effectively mediate any information that they disclosed to the participants with lower access levels. One participant stated that the conceptual view provided a solution to speed up the process of having to work with the data owner verbally to determine the optimal well placement. Selective disclosure of information about a completely obscured region of data through verbal communication during a real-time collaboration session is faster than working with a sanitized dataset offline and using asynchronous verbal communication to collaborate. However, it is not as fast as dispensing with protection mechanisms and collaborating over unobscured data in real-time. This user thought providing a conceptual view that shows enough context to orient the discussion around structures in the data provided an excellent compromise between speed of collaboration and security. All participants rated the chance of them using a tool like this for real collaboration scenarios between four and five on a scale of one to five. The only major criticism was that the virtual reality headsets can become uncomfortable over time. There were many feature requests such as the ability to specify the protected region by layer of grid cells or by the region around a certain well.

Several scenarios were identified that would benefit from this tool. These include collaboration scenarios where companies are working together. Although this was historically less common it is a more common occurrence in today's highly competitive environment. The scale and complexity possible in modern large scale projects may also require close collaboration between companies. A company that has invested a large amount of resources into the processing and interpretation of data could be compromising a large competitive advantage by giving highly trained experts from an external organization unfettered access to the data. On the other hand, if the companies do not collaborate, mutually beneficial opportunities may be missed. There is always some risk and the rewards must be weighed carefully. The subject matter experts indicated that this tool does help manage this balance. Demarcating regions to apply visual obfuscation techniques is a simple method, but even this provided a capable means to restrict views of sensitive data in a convenient, obvious and usable manner. This provided a very large amount of comfort to the data owner in the mock scenario used in the evaluation.

Another scenario that was identified was for training and support. For example reservoir simulation companies may need to diagnose bugs or train staff in the use of their tools. The tool provides capabilities that could be used to demonstrate bugs or show troublesome scenarios that require guidance. This could be very quickly and safely achieved using this tool with less risk of inadvertent information disclosure and faster access to the relevant data by the reservoir simulation company than using existing methods. One participant said that the proposed solution was ”a treatment to this problem”.

7.5.2 Mixed Reality Collaboration Test

In both cases, when the data owner U_H was asked if they authorized showing the restricted view to the public display for the manager, they consented. This displayed data with the highest clearance level to the augmented reality user, circumventing the protections around the sensitive data, since the augmented reality user could clearly see the privileged data on the screen.

7.6 Discussion

This project was based on discussions with oil and gas industry experts. This prototype was built to verify if such a system could assist with the perceived need. Although only two formal feedback sessions were performed, they do provide evidence that the proposed solution would help improve efficiency when collaborating over sensitive data while providing greater control over the dissemination of information. Much like the evaluations of the prototype immersive tool in chapter four, the objective of these feedback sessions is to determine if further investigation is warranted. Exposing users to a prototype and methodically gathering feedback is a kind of exploratory analysis of the design, allowing observations, requirements and themes to emerge. These findings can then be confirmed with more rigorous studies.

One thing was made clear in the feedback sessions that were performed – this is a promising approach to solve real problems. According to the feedback received, collaboration between organizations or training of staff or interns are two specific situations directly supported by this tool. Due to the time involved with implementing meaningful features to support complex reservoir engineering workflows, it is untenable within the scope of this project to implement rich workflows that would truly test the capabilities of this system. Despite this, careful consultation with reservoir engineering students and professionals has indicated that validating a well placement within the model is a task that has enough commonality with many fundamental reservoir engineering tasks. This ensures that although simple, the task has representative characteristics of many situations that petroleum engineers would encounter. For this reason results based on this task may reasonably be extrapolated to many tasks in petroleum engineering.

A few issues were raised by the subject matter experts. The first and foremost issue that the subject matter experts raised was the variety of data that was available. In a typical collaboration scenario, the collaborators would have access to a larger variety of cell property values. The prototype provided three key data types: porosity, permeability, and pressure. In the real world the reservoir engineers would have access to many times more types of data to help assist with decision making. The subject matter experts felt that for this system to become more useful for real world practical applications it would need to include as many of these different data types as possible. Additional kinds of data such as streamlines representing flow and surface data are also desirable. This would introduce more complexity with respect to both the design and implementation of the access control policy and information protection mechanisms.

A common complaint especially among inexperienced VR and AR users is the problem of simulator sickness. This is something that for many people can be reduced through continued exposure over subsequent usage of the devices. However, in some cases the ”VR sickness”, as it is colloquially known, is something that cannot be overcome. This means that, unfortunately, for some users it will not be possible to use a system such as this one. This would result in falling back to more traditional methods of viewing data. The data protection techniques can still be applied to these more traditional methods. Some users also wanted to take breaks from the immersive headsets, as over time they became tiresome. This may be mitigated by providing access to the CAVE environment, which has been reported to be more comfortable for long periods of work due to the use of lightweight stereoscopic 3D glasses and the proprioception afforded by this kind of environment. This highlights the need to support secure collaboration across a variety of devices, such as large scale visualization environments and non immersive devices so that users may leverage the benefits of immersion but also continue to collaborate on non-immersive devices as dictated by their comfort.

The data owner in both cases was willing to show the data to the "manager" when asked, completely forgetting that the augmented reality user could see the data. When the screen is exposed, the augmented reality user can be clearly seen looking at the exposed information. A virtual reality user could peek as well, although that would be a more deliberate and obvious action. The augmented reality user is able to see any information in the room at a glance due to the transparent visor characteristic of augmented reality headsets. Also, augmented reality users may be using devices such as tablets for their augmented reality experience rather than headsets. This kind of confusion regarding interactions between the virtual and real world supports findings that show an increased rate of accidental information leakage in these environments. Benford [28] cautioned that careful attention must be paid to boundaries between spaces, and multiple boundaries may be confusing. This supports the need for careful consideration when sensitive data is shared across these boundaries and when new boundaries are formed during a collaboration. An access control policy that prevents public display of information when there lower access level participants in the room would prevent these kinds of data leakage. In particular, an attribute based policy would be extremely helpful, as it could understand the context and help prevent inadvertent disclosure of information, in a manner most relevant to the situation. Identifying discrete shared spaces, and using policy to enforce restrictions or notifications around the sharing of data between the spaces may provide great benefit. In this instance, a policy that forbids privileged views from the synthetic workspace back into the physical space via public displays with augmented reality users may prevent information leakage. This could be accomplished even with the access controls implemented in this prototype, however a formal framework that is generalizable to varied situations would provide even more assurance.

Chapter 8

Future Work and Conclusion

8.1 Future Work

Secure collaboration across the reality-virtuality continuum has been explored through some simple protection mechanisms in one scenario with two feedback sessions each consisting of three reservoir engineering subject matter experts. Although many lessons have been learned and a large amount of foundational work has been performed, much work still remains to provide secure collaboration across the reality-virtuality continuum. A deeper understanding of how the techniques may be integrated into scientific workflows in general, and reservoir engineering workflows in particular, is required. Further visual protection mechanisms should be tested, exploring a greater diversity of visual protections and a variety of applications. Further investigation is required to determine exactly how much information can be removed using visual protection mechanisms to provide a useful context for collaboration, while preventing the dissemination of sensitive details. The generalizability of these techniques could also be explored to see if consistent criteria across a variety of use cases can be developed to inform the selection of visual protection mechanisms. Support for co-located collaboration incorporating public displays, personal devices and interactive surfaces must be considered. Co-located collaboration should be integrated into a holistic solution that spans all the scenarios described in this work, while maintaining consistent collaboration and data protection paradigms. Although a simple access control system has been implemented, it should be expanded and tied into access control policy that supports the security features required across all scenarios. The required supporting infrastructure to define and administer the policy must also be developed, and may be optimized by the use of artificial intelligence to automate the definition and application of the policy. A variety of tasks must be supported to ensure effective analysis of data, and to support domain specific workflows. Ideally, these tasks would not be compromised by the addition of mechanisms to support collaboration over sensitive data. It is therefore necessary to investigate if the implemented protection mechanisms compromise these tasks, and if so find ways to ensure task efficiency is preserved. Additional security mechanisms such as encryption and authentication must also be developed to provide a complete solution. Integration with supporting infrastructure, data management tools and existing workflow management systems is also required.

8.1.1 Deeper Understanding of Requirements

Further studies are required to identify user behaviours, preferences and needs related to protecting information across the reality-virtuality continuum. Gathering this information from a variety of users across different scenarios is foundational to designing tools that are both usable and secure when collaborating over sensitive data. This requires further development of the fundamental tool, since many applications of rich policy language and novel protection mechanisms are best illustrated within the context of real-world workflows on realistic datasets. This requires more development of fundamental features of the application, so that policies and protection mechanisms can be tested within suitably complex scenarios that reflect how tools would be used in an industrial environment. Alternately, careful consideration is needed to craft scenarios and minimum implementations that can be used to validate hypotheses in representative scenarios. Although this would require less development time, it will require a large amount of time to analyse user workflows and design these representative scenarios, as has been done with the well location analysis task performed in this study.

8.1.2 Visual Security Methods

Only one visual protection method was tested. Removal of all colouring that provides information regarding property values and restricting probing used to obtain precise information was a sensible choice that clearly supports the concept of structure without detail. However when examining visual privacy protections used in multimedia, many different methods were used such as cartooning, blurring and selective modification of the data. The application of these methods and evaluation of their effectiveness in protecting information or data as needed, while still providing enough information to provide a useful collaboration tool, could be explored. If the method is not effective at protecting information, then it will not support the goal of restricting the flow of information. If the method can not provide some information, there is no benefit to using the method, since it would be equivalent to simply blocking the information from view. Investigation is required to find visual protection methods that provide a useful conceptual view, while still ensuring data or information that must be protected is not communicated to the wrong parties. Utilization of various methods of abstraction [318] could be used to simultaneously improve the perception of some features, while reducing the fidelity of some information to a point where it provides utility as an information security mechanism. These methods must be designed and evaluated both for fitness as a security mechanism, and as useful tool that uses different techniques to provide conceptual views that may illustrate specific concepts even more effectively than a high-fidelity view. Determining suitable metrics that can be used to assess both of these aspects of the visual protection mechanisms must also be developed.

8.1.3 Usability Studies

To understand the broader usefulness of these techniques, it would be beneficial to perform in-depth studies on various tasks to see what effect the asymmetry of information has on these tasks. Usability can be defined as "ease of use" plus "usefulness" to the user. More specifically, this includes quantifiable characteristics as learnability, speed and accuracy of user task performance, user error rate, and subjective user satisfaction [35]. Both the usability and the effect on security and privacy during collaboration of protection mechanisms must be investigated. This may reveal factors that contribute to or hinder collaboration using these kind of visual protection mechanisms.

8.1.4 Solutions for Co-located Collaboration Spaces

Although the reservoir visualization tool can be used in a large scale visualization system such as a CAVE, the visual protection mechanisms would not work in this environment since there are not different views for each user. An investigation into how to best restrict the flow of information and authenticate users and their locations would be a useful extension to the tool, so that protection mechanisms used in the head mounted versions can extended to co-located visualization environments. Utilization of proxemics [116] to create privacy zones may be used, perhaps with techniques such as Bodylenses [153]. Techniques such as those found in [42] may be incorporated into this solution to protect information. Integration of other technologies such as interactive tabletops, mobile tabletops, passive displays and implementation of a holistic solution that allows for collaboration utilizing these technologies as well would increase the applicability and usefulness of a solution.

8.1.5 Integration of Security Policy

As more insight is gained into user needs and preferences, this will elucidate the contexts that are important to capture in the security policy. This includes understanding the attributes that must be collected from the environment, the subjects, and objects, and how to use those attributes to make access control decisions. This will drive further investigation of possible areas for access control policy research. Access control models have undergone a large amount of evolution [141], however, many challenges still remain even within Attribute Based Access Control [271] including the administration, delegation and scalability of ABAC implementations. Further investigations into how to apply ABAC or ABAC based policy frameworks to these systems is needed.

Given that many fields utilizing scientific data are subject to institutional or governmental compliance, investigation into how to apply compliance verification in these collaborative scenarios is also required. While some works have attempted this [142] there is little understanding of how to incorporate these methods into a tool like the one described in this work.

Extending the basic policy logic would also be extremely important to cover a wider range of tasks and contexts that would emerge as these techniques are used in different scenarios and on different devices. As more contexts emerge through an exploration of extended reality collaboration in a variety of scenarios, then the supporting attributes must not only be identified, but the policy framework that should be implemented is also important to determine. Infrastructure to support the access control policy such as tools to administer and define the policy are also required. Artificial intelligence techniques may also be applied to assist users with policy definition and application.

8.1.6 Integration of Usable Security Principles with other Frameworks

The benefits of collaboration in a visual analytics setting have been discussed. However, more attention to how secure collaboration could be developed into a framework is needed. Combining the security concerns with visual analytics design considerations [121], for instance, could allow the integration of usable security principles with visual analytics best practices to provide a tool that enables secure collaboration, with the minimum of impediment to visual analytics workflows. This would allow highly effective analysis and collaboration tools, while still providing sufficient control over information dissemination to encourage users to collaborate.

Integrating security considerations within a framework of abstract visualization tasks [40] could be beneficial. A security framework could be developed that integrates each of these abstract visualization tasks with protection mechanisms in a reservoir visualization context. Attempts have been made to integrate Activity Theory into Visual Analytics workflows [83], and this work could be extended to consider security concious workflows in visual analytics as well.

8.1.7 Additional Security Considerations

It is also important to understand how to integrate the various security components such as authentication, detection of relevant contexts, policy interpretation and implementation of protection mechanisms into the application so that usable collaboration scenarios are enabled while ensuring the needed protections are in place.

For example, it would be worthwhile to find an effective authentication mechanism that provides a continuous and secure authentication session that can adjust to the needs of the application as contexts are changed. In extended reality collaboration, there may be new contexts as users or devices are added, or even as devices are removed. Therefore, an authentication solution that can re-authenticate as the context changes is more effective at maintaining a high level of security than authentication that occurs only at the beginning of the session. Some possible solutions that could be tried have been identified, such as wearable technologies that use continuous monitoring of biometrics.

Other aspects of protection that have not been integrated into this application include encryption, and a robust back-end architecture. Integrating cryptographic enforcement of conceptual views, such as has been done for secure scrambling of images [336] could be one possibility. Integrating attribute based encryption techniques [109]. In particular a system such as Sieve [324] which uses attribute-based encryption to translate human-understandable access policies into cryptographically enforceable restrictions would be a good integration.

8.1.8 Integration into Scientific Computing Infrastructure

While this work has focused on how to integrate security considerations in to an immersive collaboration environment, no attempt has been made integrate this work with common infrastructure found in scientific computing environments. In particular, effective integration with scientific workflow management systems [64] and integration with data management systems such as those supporting data provenance would allow for a more comprehensive solution, since control of information dissemination could be applied to historical changes to data [339] as well as historical insights [108]. This would support very important aspects of a real collaboration system, and would vastly improve the real-world functionality of the secure collaboration mechanisms. More complex contexts could be evaluated, and additional protection mechanisms could be implemented, such as controlling where data is rendered, as discussed in Appendix B. Integration into real-world systems would also allow for an evaluation of the scalability of the system in a variety of contexts.

8.2 Conclusion

A workplace environment can have complex privacy requirements and diverse user groups with different backgrounds and expertise. Both personal and business data must be protected in scenarios that may require collaboration with social or time pressures encouraging bad privacy behaviour on the user's part. It is critical to consider how individual differences in concerns, preferences and behaviours may impact a variety of design decisions such as: choice of technologies that may be safely incorporated into workflows, access control models that support the user requirements in these environments and how authentication may occur. In doing this, workplaces may adopt immersive technologies while ensuring the protection of employees and the safety of their data.

This work has articulated the development of a tool for immersive reservoir visualization, showing how immersive technologies may be used to provide value when analysing static data and well placements in reservoir engineering. This tool has been evaluated by a variety of professionals, researchers and students from the oil and gas industry. This evaluation has supported the value of immersion in reservoir engineering, the effectiveness of the occlusion management techniques and the ability for an immersive work tool to promote a state of flow. Collaborative capabilities supporting using a variety of virtual and augmented head mounted displays as well as a CAVE have been added to enhance the value further and show how immersive technologies can be used to collaborate over data.

A variety of scenarios have been discussed within the context of secure collaboration. These scenarios include co-located collaboration, virtual reality collaboration, augmented reality collaboration, and mixed reality collaboration where physical and virtual spaces are connected to present an integrated collaborative space for remote and co-located collaborators. This provides an understanding of some representative scenarios to explore the use of technologies across the reality-virtuality continuum when collaborating over sensitive data. The integration of a variety of different spaces requires clear identification of boundaries between spaces and how information permeates through the boundaries. Cues allowing users to understand exactly who they are sharing information with across spaces and what different users can see must be maintained. Finally, highly dynamic security contexts must be supported, as the security context can change as new spaces are added, properties of boundaries between spaces change, devices are added, data or information is introduced, sensors are activated, or the composition of identities or roles change across any of the spaces. The location of where processed information, such as visualizations, must be displayed, supporting infrastructure used, amount of control over endpoints and trust in computer networks also influences the security context. This requires access control policy that can incorporate a variety of contextual information about the users, the data and the environment to control access to information. Attribute based access control (ABAC) is one such access control policy that authorizes access to information based on subject (user) attributes, object (data) attributes, and environment attributes. ABAC is more complex to implement than access control polices such as role based access control (RBAC). Despite this, ABAC has seen increased acceptance in industry due to its support for dynamic, attribute based contextual authorization. Mechanisms such as context aware access control policy may be used to help users "do the right thing", in the face of increased complexity. This could include denying risky information sharing across boundaries into spaces where identities can not be properly authenticated or where portals into other unknown spaces may exist. This access control policy could be combined with continuous authentication mechanisms which provide transparent authentication mechanisms that are convenient for multi-device collaboration and immersive environments, and ensure authenticated identities in a collaboration session are always current and accurate.

Effective collaboration across the reality-virtuality continuum involving sensitive data requires enough information be shared so that collaborators can effectively collaborate, even with users that have lower levels of access to data. However, the dissemination of information must be controlled, so that the principle of least privilege may be upheld and information disclosure can be mediated by the data owner according to their preferences and the needs of the collaboration scenario. This objective can be accomplished through the use of access control, access control policy and visual protection mechanisms that provide clues regarding the nature of content or illustrate conceptual details to lower-privilege users so that collaboration can occur, while removing sensitive detail.

A secure collaboration tool utilizing immersive technology designed to provide more control of information and more effective analysis of reservoir data than existing tools has been developed and evaluated. This has provided many insights and created the infrastructure for additional ideas to be implemented, tested and evaluated. Visual protection mechanisms have been shown to have potential to solve a variety of collaboration scenarios involving sensitive data in reservoir engineering. This includes training and education, research collaborations, reservoir simulation software support and collaboration between different organizations. The potential for inadvertent information disclosure reported by others involving mixed reality collaboration scenarios has also been demonstrated in these evaluations. In both evaluations, the data owner was tricked into revealing sensitive information to a user with a lower level of access.

As technology evolves and becomes more ubiquitous, it is important to consider how it could be integrated into existing tools and processes. However, it is equally important to evaluate both the security implications and the usability of these systems in general. Ideally the usability and security implications will be holistically explored, so that these technologies can be integrated in a manner that provides a high-quality user experience as well as a functionally secure system across many scenarios. There are many unsolved challenges remaining to integrate usably secure immersive collaboration tools into real-world scientific computing environments. Despite this, much progress has been accomplished, and the lessons learned in this undertaking are generalizable and will help others grappling with how to design and develop secure yet usable industrial tools using these technologies.

As a use case, the Energi Simulation / Frank and Sarah Meyer Collaboration Centre will continue to integrate the technologies developed to support collaboration over sensitive data and apply the lessons learned. Additional features will be added to the reservoir engineering tools, and additional protection mechanisms will be prototyped, assessed, and applied to the additional features. Features and protection mechanisms such as utilization of proxemic interactions to maintain privacy will be assessed for usability and protection techniques will be applied to support other collaboration scenarios, such as co-located collaboration. Access control policy infrastructure will be implemented and applied to a variety of protection mechanisms, including a variety of visual protection mechanisms and to prevent risky dissemination of sensitive information across shared space boundaries or to untrusted devices. As visual and immersive analyics tasks are integrated to support engineering workflows, studies will be performed to ensure that the security mechanisms preserve these tasks as much as possible. The addition of transparent and convenient authentication mechanisms, encryption and other security components will provide a more holistic secure collaboration tool. Integration with high performance computing (HPC) and high-end data analyics (HDA) resources will require integration with scientific computing infrastructure, however, this is also required to achieve a complete solution.

Other visualization centres may use the lessons learned in this work and equip their facilities to provide a visualization and analysis ecosystem that includes a variety of devices across the reality-virtuality continuum, including interactive display environments, head mounted displays, and public or personal interactive surfaces. Ideally, users should be able to move workflows easily from devices to large scale visualization infrastructure as needed. In order to unlock the value of this equipment It is important to ensure that effective, usable and consistent collaboration tools can make use of a variety of devices while providing mechanisms that help users avoid inadvertent disclosure of information. These tools should support collaboration rather than impede it by enabling allowing users to maintain the principle of least privilege and mediate the flow of information according to needs and preferences.

Appendix A

Post-task Interview Questions

Interview ID	
Reviewer Name	
Subject ID	
Subject Background/Specialization	
Date of interview	

Collaborating over scientific datasets is a key part of a modern reservoir engineering workflow. Immersive visualization hardware such as virtual and augmented reality is currently being examined by the oil and gas industry for a variety of applications including reservoir engineering. These immersive technologies provide both a potential opportunity for more efficient collaborative tools as well as potential security risks. These risks may stem from a lack of user familiarity with the technology, as well as weaknesses with existing access control policies that do not adequately capture the complexities of these scenarios. We hope to explore some potential solutions to these security risks by applying advanced access control policies to collaboration scenarios using immersive technologies. This may enable control of information appropriate for these scenarios, allowing more effective collaboration by ensuring that the information that must be shared can be shared effectively, while the information that must be protected may be safeguarded. The following is a sample semi-structure interview aiming to gather general feedback/comments from the participant and any suggestions he/she may have regarding improving our system. The participant may ask to clarify any question and more explanation will be provided, and he/she can decline to answer any question. For your interest, this part may take up to 30 minutes.

Thank you very much for your time and effort!

1. Do you think that the scenario you were given is an accurate representation of a collaboration that could occur in an industrial setting?

2. How do you currently collaborate over data or scenarios such as the one in this study?

3. With whom would you typically collaborate?

4. How is this collaboration typically accomplished currently?

5. What are your security concerns regarding collaboration over this kind of data?

6. Are there situations you have encountered where you want to collaborate over data but would like to withhold some aspects of the dataset from your collaborators?

7. How often does this occur in your experience?

8. Does concern over sharing a certain part of a dataset ever prevent you from sharing the whole dataset and thus not collaborating and communicating as effectively as you would like?

9. Based on your experiences in this session, do you think that immersive technologies such as virtual and augmented reality could be a good medium for collaborating over reservoir data?

10. Do you think that the prototype could provide any advantages over the current means of performing this kind of collaboration? If so what are these advantages?

11. Do you think that there are any disadvantages of using this prototype over the current means of performing this kind of collaboration? If so what are these disadvantages?

12. Do you feel that you were able to control information effectively in this prototype? Specifically, ere you able to share what you needed to share and withhold the information you wanted to withhold?

13. Did you gain a greater understanding of how information leakage may occur using immersive technologies?

14. Did you feel that our prototype mitigated this potential information leakage? Why or why not?

15. Please provide a general comment about our learning system (e.g., what I liked, what I did not like, things to be improved, etc.)

Appendix B

Client vs Server Rendering Example

Introduction

Many fields deal with sensitive data that may only be disclosed according to constraints such as government regulation or corporate policy. While there has been a great deal of research on how to visualize and collaborate for knowledge discovery, there is a much less work investigating how to collaborate without compromising operational security [60]. Another complication is the desire to distribute data processing to assist with responsiveness and to combat issues of scale when dealing with modern scientific data sets. Some examples include a high performance web-based system for analyzing and visualizing spatiotemporal data for climate studies [188] and a client-side web application for interactive environmental simulation modeling [322]. These two examples are representative of a growing number of tools that seek to provide high quality interactive scientific discovery by distributing data. With this in mind, the ultimate goal is to develop a viable system that will combine effective access control and effective protection of information in order to support collaborative scientific discovery in a distributed collaboration environment. Such a system would ideally allow rapid formation of a clearance based on security policy and based on the clearance allow for rapid identification of the data sets and collaboration tools available. Such a scenario would allow for effective collaboration and information dissemination while maintaining enforcement of confidentiality and integrity requirements. If a system can be developed with enough separation between the content distribution layer and the presentation layer, this could provide a flexible and extensible system that can meet the demands of new and complex methods of data exploration.

Background

While this initial prototype demonstrates application of simple security controls to the distribution of data, it is hoped that future work may address much wider concerns. Security concerns are currently a barrier to collaboration [268]. However, a useful solution to this issue must consider the context in which it may be used. This requires understanding the work flow and data management tools that are used to manage scientific data as well as the existing visualization tools and techniques. A valuable contribution must not duplicate already available functionality. The contribution should also have a way of integrating with existing data management and visualization tools in order to leverage their functionality or have a clear reason not to. For this reason existing scientific data management and visualization work flows must be considered.

There are several tools that exist such as VisIt [55] and Paraview [154] that support visualization and there have been attempts such as [160] to use them to build collaborative environments. However it is acknowledged that there is much work to be done and there is little mention of security concerns. There are tools to support scientific work flow and provenance [49] such as VisTrails [278]. Tools such as Globus have been used to build collaborative science applications [11]. Works such as [195] have considered intermediate data placement strategies for scientific data in the cloud. An attempt has been made to build a collaboration based cloud computing security management framework [8]. Works such as [120] consider security aware resource management strategies for work flows, however they do not specifically integrate into visual collaboration tools to allow the flexibility of client or server rendering based on attributes.

Methodology

The prototype visualization tool was developed primarily using the Django web framework [78]. The built in Django user classes are extended to support any additional fields needed for authorization of protection mechanisms. Upon successful authentication, authorization may be granted to send the dataset to the client browser for rendering. If a user is not authorized for client side rendering, images are generated on the server and sent to the browser.

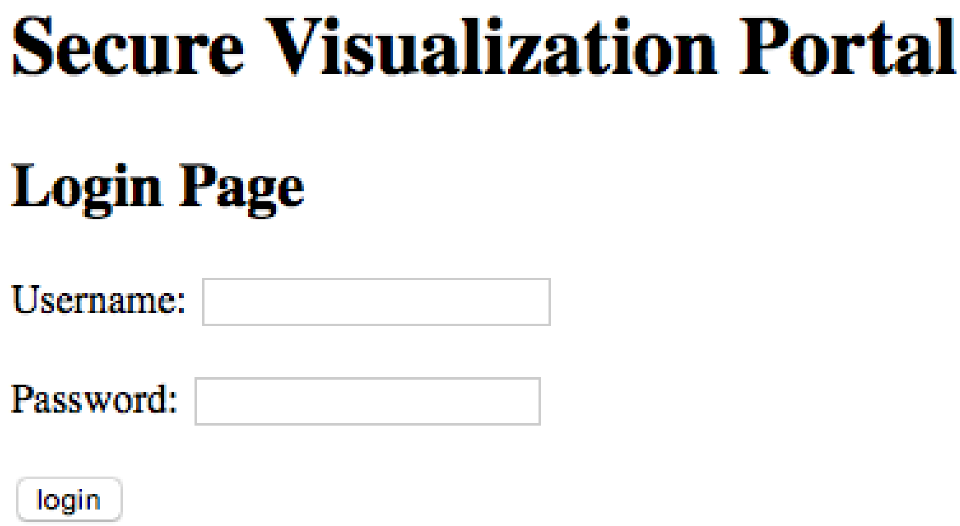

Figure B.1: View of the portal login.

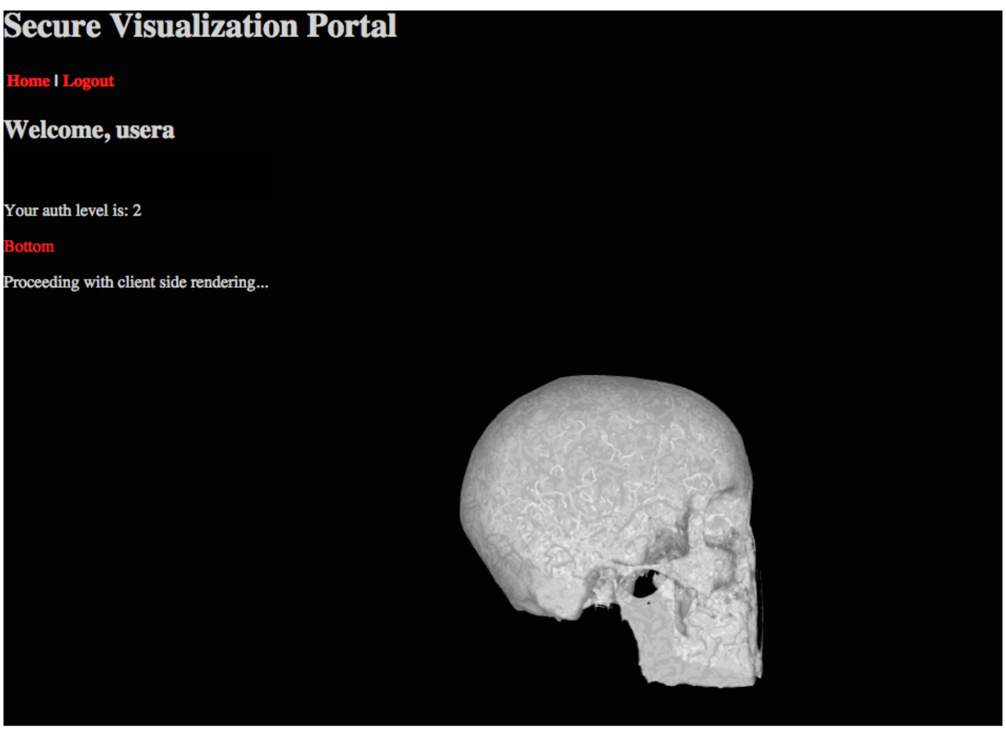

Figure B.2: View of the portal with client rendering.

The data is a 9.2MB VTK Polydata file that consists of 131284 points with triangle strips defining the topology. This represents a human skull and is a freely available dataset.

```
vtk output
ASCII
DATASET POLYDATA
POINTS 131284 float
33.9205 43.7674 -117.036
34.1211 43.01 -116.948
30.1388 50.7423 -117.066
--
-13.1175 -37.4631 67.5153
-13.1173 -37.4629 67.5154
-13.1174 -37.4632 67.5155
TRIANGLE_STRIPS 56141 418277
89 2 0 1 3 178 5 410 179 ... 1494
44 5 3 4 0 191 2 ... 683
59 5 4 179 180 411 728 ... 5068
--
3 124587 124581 124632
3 124586 124634 124591

POINT_DATA 131284
NORMALS normals float
0.0467201 0.021438 -0.998678
0.0514398 -0.200641 -0.978313
-0.0709501 -0.132886 -0.988589
```

Figure B.3: Description of Data

Client Rendering

When a user is successfully authenticated and authorized for client rendering, the client rendering tool uploads the entire data file to the client browser where it is rendered via WebGL [150] the X Toolkit [115] is leveraged for the majority of the visualization functionality.

Server Rendering

VTK [155] was used for the server side visualization. Off-screen rendering of data on the server was accomplished via the Mesa 3D Graphics Library [210]. When the visualization is requested, images are generated at five degree increments along two axis. Users may then view the images via a client side image browser that cycles through the images based on mouse movements.

Results

While there is a delay while waiting for the data to load, the user is able to enjoy a highly interactive experience once data has been loaded and processed on the client. Server side rendering provides a much less enjoyable experience, however further work optimizing the server side rendering system should result in an acceptable user experience. There is less computation required on the client with the server side rendering however. Performance considerations aside, this is a basic demonstration of the potential provided by applying security policy to protection mechanisms relevant to collaborative scientific discovery.

Conclusion

Collaboration and visualization of data are key to insight. Insight is the foundation for scientific discovery. Unfortunately, agile collaboration can be complicated both by the increasing volume, velocity and complexity of data as well as complicated relationships between different regulations, legal agreements and user preferences. By clearly identifying gaps between the current state of scientific data management and the desired future state it is hoped that tools may be developed to address this gap and provide effective access controls and a mapping between clearance levels and appropriate protection mechanisms. As a first step and proof of concept towards this goal, a prototype visualization tool has been developed that supports visualization on the client browser or on the server only, depending on the authorization level of a user. While this is a simple example of applying security policy to control a collaborative visualization tool, many exciting future extensions of this work have been identified so that this prototype may become part of a greater secure collaboration ecosystem.

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