iVirtualWorld: A Domain-Oriented End-User Development Environment for Building 3D Virtual Chemistry Experiments

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Abstract

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Virtual worlds are well-suited for building virtual laboratories for educational purposes to complement hands-on physical laboratories. However, educators may face technical challenges because developing virtual worlds requires skills in programming and 3D design. Current virtual world building tools are developed for users who have programming abilities. Nevertheless, many virtual world users (e.g. chemistry or biology teachers) neither have nor are expected to learn programming skills. This situation has been a barrier to broader adoption of virtual worlds in education. This dissertation seeks to ease the process of building virtual laboratories by applying End-User Development (EUD) technologies. A domain-oriented end-user development environment has been designed and developed for educators to create virtual chemistry experiments. This solution uses domain-oriented end-user interfaces and multi-level adaptation to enable end-users to create and modify virtual experiments according to the requirements. Case studies and usability studies have been conducted on participants from the target audience, mainly educators, to evaluate this solution on learnability, efficiency, effectiveness, and user satisfaction. Twenty-eight out of 32 participants of the usability studies were able to build a 3D virtual chemistry experiment within one hour. The solution was considered easy to learn by 80% of the participants and easy to use by 52% of the participants in the

usability studies. A comparative case study revealed that the solution was more straightforward and less distracting than a commercial system. The contributions of the work presented in this dissertation include: 1) it develops a new tool for non-technical end-users, especially educators, to build virtual experiments without programming or 3D modeling skills; 2) it extends the application of EUD technologies to 3D virtual chemistry experiment domain and provides research experience on the area of EUD tools; 3) it applies domain-specific modeling technologies and, as the result, a domain model of chemistry experiments has been sketched up and implemented in 3D virtual environments; and 4) it conducts empirical research and collects experimental data for evaluation and analysis of the usability of the proposed solution.

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Table of Contents

List of Tables

List of Figures

List of Acronyms

3D	Three Dimensional
BooKS	The Boat-of-Knowledge in the Science Classroom
EUD	End-User Development
FBX	Filmbox
HTTP	Hypertext Transfer Protocol
IDE	Integrated Development Environment
IQR	Inter-Quartile Range
IRB	Institutional Review Board
LSL	Linden Scripting Language
MySQL	My Structured Query Language
NMC	New Media Consortium
PHP	Personal Home Page
TDS	Total Dissolved Solids
VRML	Virtual Reality Modeling Language

1. Introduction

Laboratory activities play an important role for science education, especially in chemistry, physics, biology and engineering. This is because that concepts and theories of these disciplines must be obtained by students not only from passive learning (e.g. listening to lectures and taking notes), but also from active perceiving, observing, and practicing during laboratory activities. Traditional on-campus education provides students with hands-on experiments in laboratories equipped with experimental instruments. However, hands-on experiments have several limitations such as limited resources (e.g. physical space, teachers and open hours) for students (Ertugrul, 2000; Lagowski, 1989), safety issues during experiments (Bell & Fogler, 2004; Chen, Song, & Zhang, 2010), and expensive instruments and materials (Domingues, Rocha, Dourado, Alves & Ferreira, 2010; Ma & Nickerson, 2006). These limitations can adversely influence the effectiveness of science education because of insufficient laboratory resources for students and teachers and high investments for educational institutions. Furthermore, hands-on laboratory experiments bring huge challenges to schools that also offer online or distant learning courses to students (Chen et al., 2010).

Educators have been seeking solutions to complement real world laboratories for decades using new emergent and developed computer technologies. Virtual laboratories, based on computer graphics, computer simulation and computer networking, were proposed and studied by researchers from education and computer science. Although there are claims that virtual laboratories cannot replace real world experiments entirely, virtual laboratories have significant advantages over traditional real world experiments:

virtual laboratories can be accessed from anywhere at anytime, particularly suitable for distance learning students (Jensen et al., 2004); virtual laboratories are safer (Chen et al., 2010; Martinez-Jimenez, Pontes-Pedrajas, Polo, & Climent-Bellido, 2003; Woodfield et al., 2005), quicker to finish (Woodfield et al., 2005) and cost-effective (Chen et al., 2010; Martinez-Jimenez et al., 2003); virtual laboratories can present experiments under idealized conditions (Martinez-Jimenez et al., 2003). Studies have provided evidence that the virtual laboratory as a complementary tool to real world laboratories can increase students' performance (e.g. problem-solving skills and cognitive skills) in the class (Baher, 1998; Martinez-Jimenez et al., 2003; Woodfield et al., 2005).

Studies on virtual laboratories can be dated back to 1970s (Chabay & Smith, 1977). Virtual laboratories varied from single user standalone computer systems to distributed or web-based applications, and from text-based experiment simulations to 3D interactive simulations. Virtual laboratories applied various technologies such as Flash (Domingues et al., 2010), Java 3D (Bell & Fogler, 2003), Virtual Reality Modeling Language (VRML) (Bell & Fogler, 2004; Jensen et al., 2004), and Microsoft Visual Basic (Martinez-Jimenez et al., 2003).

In this decade, the development and the popularity of 3D virtual worlds provide platforms that extend the usefulness of virtual laboratories by putting students into multi-user virtual environments that can simulate real learning environments. Three-dimensional Virtual worlds (3D online multi-user computer programs that simulate real-world environments) have been identified as technologies that can facilitate education. The simulating ability of 3D virtual worlds shows advantages when applied in training of operations that are dangerous such as underground mining (Nutakor, 2008). Each user joins a 3D virtual world through a visual representation called an avatar, which improves the perception of users inside virtual worlds and motivates play in virtual worlds (Mikropoulos, 2006). Navigable and interactive 3D environments could better help students to develop spatial knowledge than non-interactive and non-3D alternatives such as 2D pictures, videos or panoramic photographs (Dalgarno & Lee, 2010; Trindade, Fiolhais & Almeida, 2002). Applying 3D virtual worlds also brings benefits on modeling the full physical behaviors of objects (Dalgarno & Lee, 2010). Another advantage of 3D virtual worlds is the simulation of experiments that could not be performed in the real world e.g. simulations of molecular reactions (Holloway, Fuchs & Robinett, 1991; Trindade et al., 2002). Furthermore, 3D virtual worlds could be transformed to 3D augmented reality by integrating hardware such as head-mounted displays (Holloway et al., 1991) or Cave Automatic Virtual Environment (Dalgarno & Lee, 2010). Virtual worlds also provide a social platform for users to express their creativity, share information and communicate with each other. With these features, virtual worlds can be adopted to create virtual laboratories as a complement to traditional hands-on laboratories to overcome the limitations of the latter.

Although 3D virtual worlds show great potential in building virtual laboratories for educational use, educators are facing difficulties applying 3D virtual worlds (Chou & Hart, 2010) as they wish. We believe that 3D virtual world technologies can bring many benefits to education if they are applied sufficiently and can provide proper environments for conducting virtual experiments. This motivated this study to seek a solution to assist educators in the process of building virtual laboratories easily by themselves.

End-User Development (EUD) is the study of methods, techniques and tools enabling non-technical computer end-users to create or modify a software system to reflect their requirements. Research in EUD integrates Human Computer Interaction, Software Engineering, Computer Supported Cooperative Work, and Artificial Intelligence. This is a research area derived from End-User Programming, making the shift from “programming” to “development” (Repenning & Ioannidou, 2006b). One challenge for research on end-user development is "to develop environments that allow users who do not have a background in programming to develop or modify their own applications, with the ultimate aim of empowering people to flexibly employ advanced information and communication technologies" (Lieberman, Paterno, Klann, & Wulf, 2006). In the domain of chemistry experimental education, educators are end-users who typically do not have a programming background. Their applications are 3D virtual chemistry experiments for educational usage. This study will apply EUD technologies in chemistry education and design a solution for educators to build and modify 3D virtual chemistry experiments easily and flexibly based on the needs of their students.

1.1 Statement of the Problem

Previous studies have shown both benefits and issues of educational applications of 3D virtual worlds. One significant issue concerns the technological difficulties of creating and using 3D virtual worlds (Chou & Hart, 2010; Woodfield et al., 2005). In order to render simulated scenes on computer screens that resemble the real world, 3D virtual worlds apply computer graphics and related technologies. These computer graphics concepts that are integrated into 3D virtual world building tools are obscure to teachers. In addition, enabling the animation of one 3D object or the interaction between multiple objects in 3D virtual worlds requires non-trivial programming efforts. Most computer end-users lack the training in programming and have no time to learn scripting used in 3D virtual worlds. Three-dimensional virtual world technologies bring the steep learning curve, which becomes a barrier for end-users who have the need to apply 3D virtual worlds (Chou & Hart, 2010; Indraprastha & Shinozaki, 2009). For example, Second Life, one of the most popular virtual worlds has been commented as “a complex open platform to be creative and for building 3-D spaces and items” but ”can be difficult to use with its steep learning curve for creating virtual items” (combinedstory, DMD New York, & Market Truths, 2007). In an online survey conducted by New Media Consortium (NMC) (Levine, 2010), an international not-for-profit consortium of learning-focused organization, ”learning curve” was identified by most of the 273 responses as the answer to the question “What is the number one barrier to broader adoption of virtual worlds by your institution?”

The statement of the problem is summarized as:

The steep learning curve of virtual world building tools has hampered wider application of virtual worlds in the educational domain, specifically virtual laboratories, which are an important complement to laboratory-based scientific education.

Steep learning curves imply that 3D virtual world building tools are difficult for non-technical computer end-users to learn and use because of the complexity of the tools and high technical requirements (Levine, 2010). It also implies a time-consuming learning process and heavy learning burden. End-users are willing to take advantage of the merits of virtual worlds to facilitate their daily work. Nevertheless, it is unrealistic for them to learn 3D virtual worlds building technologies such as 3D modeling and programming. Once they find out that it is difficult to learn these tools, they tend to give up and stick with traditional teaching methods no matter how amazing these tools could be.

This study proposes a solution to apply EUD techniques to smooth this learning curve to make building 3D educational virtual worlds easier and quicker, which helps broaden adoption of virtual worlds in education.

1.2 Purpose of the Study

One purpose of this study is to explore the application of EUD in the area of 3D virtual worlds authoring. The development of 3D virtual worlds requires high-level 3D modeling and computer programming skills that are not possessed by the average computer users. However, average computer users use the virtual worlds but have no ability to modify them according to their requirements. EUD provides technologies that can be applied to address this problem. Other researchers have applied EUD technologies in domains such as the automation (Prahofer, Hurnaus, Schatz, Wirth, & Mossenbock, 2008) and computer science education (Kelleher & Pausch, 2005). The work presented in this dissertation extends the application of EUD technologies to another domain, which is the building of 3D virtual educational environments.

The second purpose of this study is to provide a workable solution that can smooth the learning curve, by using techniques from the research area of EUD. A new EUD tool has been implemented based on the solution, making building 3D virtual worlds, especially virtual laboratories easier than current virtual world building tools for educators.

The third purpose of this study is to conduct empirical research to evaluate the usability (measured as learnability, efficiency, effectiveness and user satisfaction) of the proposed solution. The impact of this solution on the application of 3D virtual worlds in education is also investigated.

This study is specific for the application of virtual worlds in virtual laboratories and aims at educators as the audience. However, the outcome of the study can be extended and adapted in other domains.

1.3 Significance of the Study

This study explores a new way of building virtual laboratories for general chemical education. Previous published work seldom focuses on the improvement of tools for building virtual laboratories. Most prior studies applied general-purpose virtual worlds to generate virtual laboratory scenarios. The work presented in this dissertation has developed a virtual world building tool, integrating easy to learn and easy to use interfaces and orienting to virtual chemistry laboratory domain. With the solution, educators should be able to flexibly and easily create introductory level chemical laboratory scenarios.

This study extends the application of EUD to the domain of 3D virtual worlds. By designing and developing a EUD environment for end-users in the chemistry experimental education domain, this study contributes a domain model, an EUD environment, and empirical studies to the EUD research field.

This study also gathers empirical evidence to evaluate the usability (measured in learnability, efficiency, effectiveness, and user satisfaction) of the proposed solution with non-professional users (e.g. high school science teachers) as subjects. The findings obtained from this study could be extended and adapted to other laboratory-based disciplines.

2. Literature Review and Related Work

As introduced in chapter 1, the main purpose of this dissertation is to devise a new solution that eases the creation of 3D virtual laboratories with chemistry experiments, which in turn broadens the application of 3D virtual worlds in education. End-user development technologies are employed to construct such a solution to provide an easy to learn and easy to use tool for creating 3D virtual laboratories. This chapter presents an overview of previous related work in these relevant research fields: virtual worlds' application in education, virtual laboratories, and end-user development.

2.1 Virtual Worlds in Education

With the development of computer graphics, multimedia and broadband networking, virtual worlds are able to simulate the real world on computer screens in the form of 2D or 3D representation. The abilities of object-creating, communicating, and collaborating of virtual worlds have attracted millions of individuals to register and play inside virtual worlds (Messinger et al., 2009). Since their emergence, virtual worlds have appealed the educational domain because of capabilities to foster and facilitate online learning, collaborative learning, and immersive learning in both K-12 and higher education (Choi, 2010; Collins, Bently, & Conto, 2008; Hew & Cheung, 2010; Messinger et al., 2009; Styliani, Fotis, Kostas, & Petros, 2009; Turkay, 2010).

Researchers have applied virtual worlds to diverse disciplines such as arts (Lu, 2009; Wood, 2009), commerce (Erlenkötter, Kühnle, Miu, Sommer, & Reiners, 2008), culture (Ligorio & Van der Meijden, 2008), education (Childress & Braswell, 2006), health and environment (Cooper, Carroll, Liu, Chelberg, & Franklin, 2009; Jackson, Taylor, & Winn, 1999), and science (Turkay, 2010). Multiple educational activities can be done inside virtual worlds, including class discussion (Ligorio & Van der Meijden, 2008), gallery walk (Schendel, Liu, Chelberg, & Franklin, 2008), group learning (Chang & Guetl, 2010), and simulation (Turkay, 2010). Virtual worlds can be applied either inside classrooms or long distance (Ligorio & Van der Meijden, 2008), either for classroom (Chang & Guetl, 2010) use only or available to public through the Internet (Slator et al., 1999). Overall, positive results have been observed from these applications. Although there are issues concerning technologies, virtual worlds attracted the majority of students and educators. For instance, in Turkay's study (2010), high school students responded better understanding of scientific thinking and investigation after experiencing Second Life simulations in a science class. This experience also increased students' willingness to pursue a career in Science, Technology, Engineering and Math.

Virtual world building tools applied in education vary from commercial (Chang & Guetl, 2010) to self-developed environments (Jackson et al., 1999). Commercial products include Second Life (Childress & Braswell, 2006), Active Worlds (Ligorio & Van der Meijden, 2008), and Open Croquet (Konstantinidis, Tsiatsos, & Pomportsis, 2009). Self-developed environments utilize diverse 3D technologies such as Java 3D (Bell & Fogler, 2003) or VRML (Slator et al., 1999).

2.2 Virtual Laboratory

Recent reviews of virtual laboratories (Amigud, Archer, Smith, Szymanski, & Servatius, 2002; Ma & Nickerson, 2006) showed that most application domains fell into biology, engineering, physics, and chemistry. Virtual laboratories simulated not only real world experiments, but also provide experiences that otherwise would not be possible in the real world, e.g. entering a chemical reactor while it is operating (Bell & Fogler, 1996).

A wealth of technologies has been applied in developing virtual laboratories, including Microsoft Visual Basic (Martinez-Jimenez et al., 2003), VRML (Dalgarno, Bishop, Adlong, & Bedgood Jr., 2009), Java Applet (Jara et al., 2009), and Flash (Domingues et al., 2010), to name a few. Virtual laboratories vary from standalone desktop applications (Martinez-Jimenez et al., 2003) to web-based applications (Dalgarno et al., 2009) and from single player (Woodfield et al., 2005) to multiple users (Bilyeu, Mayles, Franklin, Liu, & Chelberg, 2007). Virtual laboratories can be presented in either 2-D format (Baher, 1998; Domingues et al., 2010) or 3D format (Jensen et al., 2004).

Domingues et al. (2010) developed Vlabs (http://vlabs.uminho.pt) for a "Chemical Technology Laboratory" course taught to the third year students from Biological Engineering in University of Minho, Portugal. Vlabs integrated textural instructions, video demonstrations, online self-tests and 2D simulations. Two laboratory simulations, developed using Flash, were provided to students who could change laboratory settings and parameters to learn the results. Although Vlabs was evaluated as useful by students, it is difficult to extend to other experiments. This is because laboratory instructors have to rely on developers of Vlabs to create every simulation using Flash from scratch.

The VRUPL lab (Bell & Fogler, 2004) was developed to provide 3D simulations on the topic of chemistry laboratory accidents, which reinforced students of the safety rules in chemistry laboratories with virtual experiences of accidents. These simulations were useful for preventing students from dangerous operations and protecting students during the experiments. However, the VRUPL was limited to the accident simulations and was less relevant to the actual experiments.

The virtual chemistry laboratory implemented by Charles Sturt University (Dalgarno et al., 2009) built a 3D virtual environment resembling the layout of the real laboratory on campus to familiarize long-distance students. Students are able to explore the chemistry laboratory, including the layout and instruments, through this virtual environment before they came to the real laboratory to conduct the actual hands-on experiments. Because the real laboratory usually had a busy time schedule, this virtual laboratory saved students' time spent on laboratory familiarization before they could start their experiments. This virtual laboratory was developed as a standalone application using VRML with Blaxxun Contact, an Internet Explorer plug-in. It was distributed in the form of CD-ROM to students, who installed the virtual laboratory and Blaxxun Contact prior to use. This virtual laboratory did not provide the functionality for students to conduct virtual chemistry experiments. However, in the evaluation conducted to assess the virtual chemistry laboratory, participants suggested that performing virtual experiments would be helpful for students to prepare for the actual laboratory.

Y Science Laboratories (http://chemlab.byu.edu/) developed in Brigham Young University contains a series of laboratory simulations for students at multiple levels including high school and college freshman and sophomore. These simulations cover multiple disciplines such as chemistry, physics, and biology. Virtual ChemLab (Woodfield et al., 2004) was one part of the Y Science Laboratories and was developed using Macromedia Director (now Adobe Director). Virtual ChemLab provides simulations on a wide range of chemical experiments that reinforce the learning of chemical theory. A yearlong study conducted by Woodfield et al. (2005), applying Virtual ChemLab in a chemistry course as a complementary to traditional real world experiments, showed improvement on students' performance such as problem-solving skills, cognitive skills and exam/quiz scores. However, the study also found conflicts between students' heavy workload and instructors' requirement when incorporating Virtual ChemLab. To balance these conflicts, extra effort was needed to adjust laboratory design according to students' feedback.

Carnegie Mellon University developed an online application ChemCollective (Yaron, Karabinos, Lange, Greeno, & Leinhardt, 2010) to help students understand chemistry concepts by conducting online activities. The ChemCollective, developed using Java Applets, provides a rich inventory of chemicals and instruments that can be used by students to carry out chemistry experiments. The ChemCollective is a single user application presenting reagent, chemicals and instruments in the 2-D form.

The Virtual Introductory Chemistry Laboratory (http://www.chemgames.com/introlab.html) is an online application to complement introductory level chemistry with virtual experiment descriptions in instructions. The Virtual Introductory Chemistry Laboratory provides 13 experiments with predesigned procedures. Students are given virtual chemicals and instruments for each experiment. Students conduct experiments by following instructions and manipulating the chemicals and instruments objects provided.

2.3 End-User Development (EUD)

EUD has been identified as “an emerging paradigm” by Lieberman et al. (2006), who noticed a change of the goal of Human-Computer Interaction from making systems “easy to use” to “easy to develop”. Developing EUD environments for non-professional computer users has become “one fundamental challenge” (Lieberman et al., 2006; Repenning & Ioannidou, 2006b) and has attracted researchers to this area.

Alice (Kelleher & Pausch, 2005) is an end user programming system for novice programmers to learn programming by building 3D animations or games. This system replaces textural programming with dragging-and-dropping graphical programming building blocks, which helps users understand programming concepts and technologies such as control flow and object-oriented programming. Alice 2 provides numerous 3D objects ready for use, as well as a modeling tool for customizing new 3D objects. Alice exhibits an uncomplicated programming interface, applying techniques such as visual programming, drag-and-drop and form-based parameter customization. However, Alice targets audiences who are programming novices having a need to learn programming primitives such as variable declaration, flow control and object-oriented concepts. So it emphasizes those concepts through its end-user interaction interfaces. For those who are not willing to learn programming, this tool still has a steep learning curve because of those unfamiliar concepts.

AgentSheet (Ioannidou, Repenning, Lewis, Cherry, & Rader, 2003) is a spreadsheet-like EUD environment used to build parallel and interactive 2D simulations. Originally prototyped in 1988, AgentSheet organizes agents instead of numbers or strings as basic building blocks through spreadsheet cells. During the process of EUD using AgentSheet, end-users define agents with attributes and behaviors. An end-user programming language Visual AgenTalk has been developed for end-users to program the behaviors of agents. The outcomes of AgentSheet could be games or simulations for communication purposes. EUD technologies, such as programming by example, domain-oriented design and incremental development, have been applied to develop AgentSheet. AgentSheet has been used by end-users in a large range, from students to scientists. This EUD environment exemplifies a successful application of multiple EUD technologies in 2D games and simulations.

AgentCubes (Ioannidou, Repenning, & Webb, 2009) extends AgentSheet to 3D space as an incremental 3D authoring tool for end-users to create 3D simulations and games. While most features of AgentSheet such as the grid-structure, agents, and Visual AgenTalk are retained in AgentCubes, incremental 3D was invented to inflate 2D images to 3D objects. Incremental 3D is a design approach with which end-users draw 2D images and gradually turn them into 3D models using "diffusion-based inflation techniques".

BioShape (Buti et al., 2011) is a 3D geometry-oriented modeling environment and is under development towards improved usability by taking advantage of End-User Development techniques at different levels. The proposed three levels of EUD activities incorporated in BioShape are customization, integration and extension. Customization level provides basic behavior parameterization of the environment and default building entities for end-users to create simulations. Integration level allows building new complex entities by gluing together default building entities. Extension level enables end-users to generate their own building entities using inflation, a technique to transform a 2D image into a 3D model invented by Repenning & Ioannidou (2006a).

Prahofer et al. (2008) developed a software framework for creating end-user development environments in the industrial automation domain. This framework has been built upon a domain-specific language Monaco and a graphical IDE to provide end-users a more “intuitive and concise” environment to develop or adapt automation systems.

Raptivity (http://www.raptivity.com/) is a commercial Windows application for end-users building learning interactions. Raptivity provides prebuilt interaction models with customizable parameters so that end-users can customize learning interactions from these models without programming and visual design skills. Raptivity outputs learning interactions created by end-users as Flash files, which can be incorporated into other tools such as PowerPoint presentations and web sites. However, Raptivity has been limited to generating only Flash files, which is a limitation to represent multi-users immersive 3D virtual worlds.

Above-mentioned systems share some common features in EUD. First, they are designed for specific domains. Second, they provide end-users domain-oriented building blocks without exposing underlying programming details. Third, parameterization is widely applied to enable end-users to adapt the system to their requirements. In addition, more complex adaptations (e.g. integration and extension) are also available for complicated requirements’ changes. EUD tools tend to be domain-specific so previous projects from other domains may not fit the domain of chemistry experimental education, but EUD techniques applied in these projects could be adapted to build a new EUD tool for end-users in the domain of chemistry experimental education, which is part of this study.

There exist tools to help end-users build virtual worlds. For example, several scripting tools are available to “ease the process of scripting” in Second Life (http://wiki.secondlife.com/wiki/LSL_Tutorial). Script Generator and Autoscript are two similar web applications that generate scripts with functions common in Second Life. Particle Script Generator supplies form-based interface for end-users to generate particle system scripts used in Second Life. Dialog Menu script generator provides web interfaces for generating menu related scripts for end-users. MiceOnABeam Visual Scripting Tool is a Windows application with graphical design interfaces, which produces Second Life scripts according to state charts drawn by end-users. Scratch for Second Life is an application for Mac and Windows that allows scripting by dragging-and-dropping graphical and modularized Second Life script primitives with customizable parameters.

Although the above-mentioned tools can ease the scripting work, these programs still expect scripting knowledge from end-users. End-users have to know how to open the script editor for an object, how to compile the scripts, and how to handle syntax errors from scripts, which are beyond the reach of average computer end-users.

2.4 Discussion

Previous work generated virtual learning environments by either choosing a virtual world platform/tool, or developing a dedicated virtual world engine. Either situation needs to create a virtual environment from scratch using primitive objects (cube, sphere, cylinder, etc.), which is a time-consuming construction process and is difficult for teachers to handle by themselves (Konstantinidis et al., 2009; Trescak, Esteva, & Rodriguez, 2010). Previous virtual laboratories were developed to conduct pre-defined experiments, which confine the scenes and processes of activities in these virtual laboratories. There is a lack of research on standard frameworks that can provide experiment components for others to design and set up other experiments. Those who want to create virtual laboratories cannot reuse virtual laboratories developed specifically for others.

In order to develop virtual worlds for their usage, educators usually collaborate with professionals from computer science. For example, the North Dakota State University World Wide Web Instructional Committee participated in several projects for teaching geology, biology and economics. A significant portion of this committee was from the department of computer science (Slator et al., 1999). This solution increased the cost since developers have to be paid to build the virtual worlds. Maintenance was also needed afterwards to change the content in virtual worlds. There were requirements from teachers to adjust or modify experiments during the application of virtual laboratories in one term or semester. In addition, extra efforts of communication and collaboration are inevitable between developers and educators (Turkay, 2010), which in some cases may cause misunderstandings. For many educators, it is unrealistic to hire others building virtual worlds for them. So they may give up if they think virtual worlds are difficult to build and manipulate.

Each previous work described above employed only one virtual world platform or development tool to build virtual worlds. There exist a number of virtual world platforms and development tools. Which one should be chosen is a critical issue. It is hard to know how long the one selected will last. If a virtual world environment is no longer available, all the users either have to transfer their virtual worlds to another platform or let them go.

Very few studies have been done on creating 3D virtual laboratories using virtual worlds and enable students to carry out experiments just like what they would in real laboratories.

In summary, the literature review so far showed that few studies have been done to solve the steep learning curve problem brought by virtual worlds in the educational domain. We have taken this incentive to a study that aims at this problem by building a framework containing pre-built, reusable components for chemistry experiments so that educators teaching chemistry can design and organize their virtual experiments flexibly according to their class plans.

3. A Domain-Oriented End-User Development Environment

Previous chapters discussed benefits of applying 3D virtual world technologies in education, especially chemistry experimental education. One barrier to the broad application is the high-technology requirements for end-users who want to build and use such 3D virtual environments. The traditional solution to this problem is the collaboration between computer professionals and educators, with educational content provided by educators and programming and modeling process conducted by computer professionals. The lack of flexibility to handle changes and communication problems could negatively influence this type of collaboration. Ideally, educators should be able to create their own educational environments because they know their requirements best. To implement this idea, there is a need for simpler development tools than traditional virtual world building tools. End-user development (EUD) is a research area providing technologies for developing tools so that end-users can modify and extend the applications they are using. The goal of this study is to develop a solution for educators in the domain of chemistry experimental education, by taking advantage of technologies in EUD.

To help end-users express desired requirements, EUD introduces domain-specific modeling and graphical languages to reduce the "communication gap between the technical view of software professionals and the domain expert view of end-users" (Lieberman et al., 2006). In the domain of introductory-level chemistry experimental education, domain experts are educators who work on and communicate with notations in this domain every day. Without knowledge in computer 3D modeling and programming, they typically do not know much about technical concepts such as programming interfaces, classes, or rotation in 3D space, which are basic skills to deal with virtual worlds customization. This “communication gap” makes it difficult to create virtual worlds according to their own requirements. The domain-oriented design with domain-specific modeling encapsulates computer science-related details and only present interfaces with the domain-specific notations. Chemistry educators can handle the domain concepts with which they are familiar and still develop their own 3D virtual chemistry experiments.

A fundamental feature of EUD environments is the modification ability with which end-users could adapt the applications to their requirements. EUD suggests three levels of modification abilities to fit diverse requirements from different end-users, from basic parameterization to complex modification. The first level is the simple customization by setting parameters or selecting choices. The second level enables end-users to integrate default pre-defined components. The third level allows end-users to extend the system by adding new components (Buti et al., 2011; Lieberman et al., 2006).

To tackle the problem identified previously, a domain-oriented end-user development environment has been designed and developed, applying domain-oriented design and multi-level adaption from EUD. The solution works as an agent between end-users and underlying virtual worlds. On one side, this environment interacts with end-users with interfaces expressing the domain-oriented language. On the other side, this environment invokes the programming interfaces of concrete 3D virtual worlds to render virtual chemistry experiments. Figure 3.1 illustrates the relationship between this environment and end-users and concrete virtual worlds.

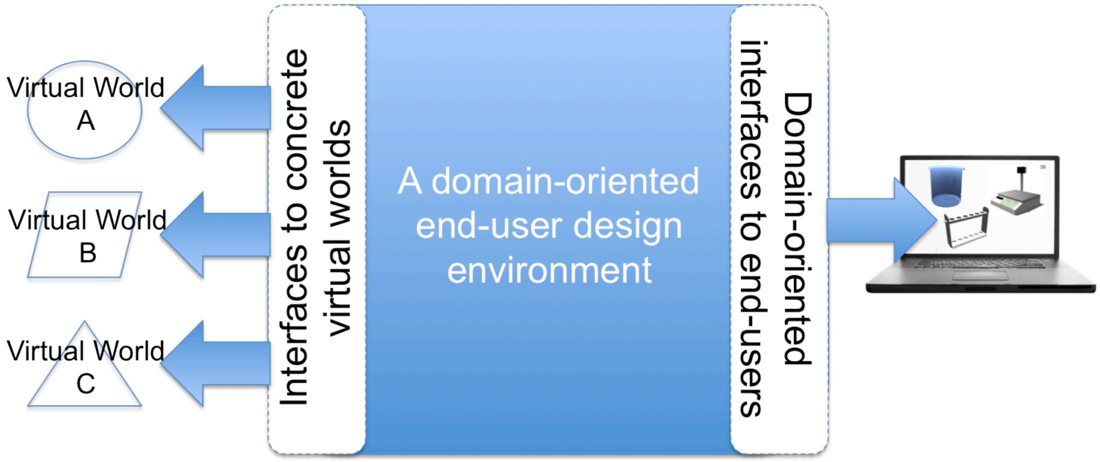

Figure 3.1: The relationship among the domain-oriented end-user development environment, end-users, and concrete virtual worlds

This chapter describes the design details of the proposed EUD tool. A prototype that implements the design discussed in this chapter is presented in the next chapter. When applying EUD technologies on the design of this tool, there are several considerations.

- Domain-oriented design: considering how to analyze the domain of chemistry experimental education, how to present end-users with domain-specific languages.
- Multi-level adaptation: considering how to provide different levels of modification to end-users to enable a smooth transition from basic parameterization to complex modification.
- Instantiation in concrete 3D virtual worlds: considering how to map the domain-specific concepts to low-level programming details.
- Communications with concrete virtual worlds: considering how to implement the communications between the proposed EUD tool and concrete virtual worlds, using computer science oriented languages and programming libraries.

The rest of this chapter discusses these considerations in detail.

3.1 Domain-Oriented Design

Because this environment interacts with users using the domain-oriented language, the domain and the basic elements of its language will be analyzed using domain modeling. Domain modeling involves identifying domain-oriented objects and possible relationships between these objects, with a domain model as an outcome for further design (e.g. creating class diagrams) and the implementation.

3.1.1 Domain Modeling

Domain experts communicate with each other through oral or written communication. They use domain-specific notations and are familiar with the relationships between these concepts and notations. However, software developers usually do not possess much knowledge of the domain in which the software they develop will be used. Domain modeling can be adopted by software developers to understand the domain-specific language, scope the system will be developed for this domain, and design the system with high reusability (Evans, 2003; Pansa, Palmen, Abeck, & Scheibenberger, 2010). Software developers inspect written materials or talk to domain experts to identify the basic elements of the domain-oriented language. This section describes how the domain model is built from the domain resources using a concrete example.

In the domain of introductory-level chemistry experimental education, laboratory manuals are documents written by domain experts and can be a good initial resource where developers extract domain-oriented notations. For example, a Total Dissolved

Solids (TDS) experiment in an introductory-level laboratory manual used by the Department of Chemistry at Ohio University (Nyasulu, 2011) is described as following:

1. Weigh an empty beaker (W_b) using a balance.

2. Transfer 1 mL unknown solution into the beaker using an autopipette.

3. Weigh the beaker with solution (W_{bs}).

4. Heat the beaker with the solution on a Bunsen burner.

5. When the water of the solution is vaporized, weigh the beaker with residue (W_{br}).

6. The TDS can be calculated using the formula: TDS (%) = $(W_{br} - W_b) * 100 / (W_{bs} - W_b)$

Notice that in the experiment description, nouns represent objects that could be used in the chemistry experiments. Some objects in the domain can stand by themselves while others have to coexist with other objects. For example, balances can be placed anywhere by themselves, but a chemical solution has to be stored in a solution container. These hidden objects are usually not explicitly described in written documents but exist as common senses for domain experts. Discussion with domain experts can help explore those hidden objects. The verbs in the experiment description usually indicate the relationship between different objects. For example, the relationship between beakers and Bunsen burners is that a Bunsen burner can heat a beaker, with or without solution in it. Figure 3.2 presents a domain model that summarizes domain objects and relationships in the TDS scenario, adopting the domain model diagram convention introduced by Evans (2003).

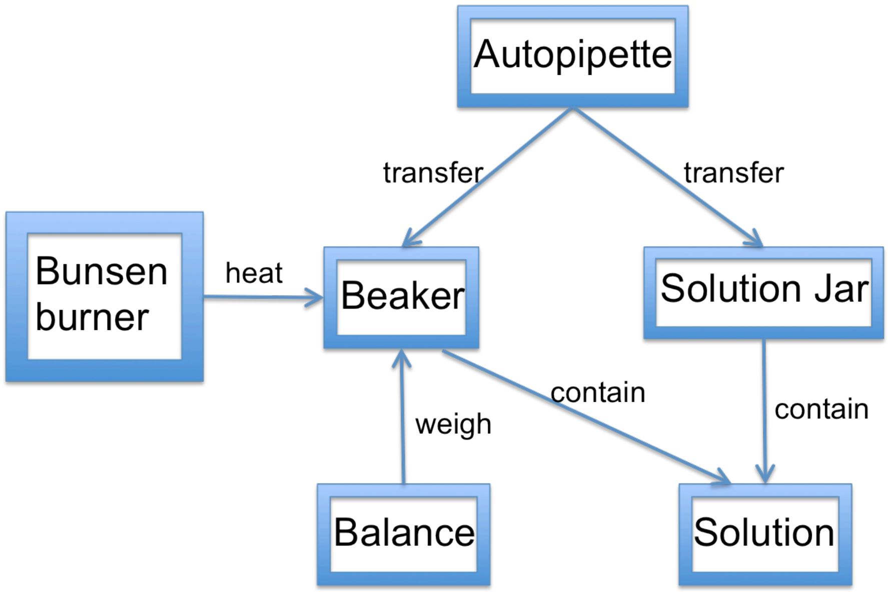

Figure 3.2: A domain model representing the sample scenario

A domain model expresses a system using the language in the specific domain. It helps software developers understand the key elements and their relationship in the domain. It also suggests the domain-oriented concepts that would display to end-users through the user interfaces. The domain model could work as a blueprint for software developers to design class diagrams and further instruct the coding. For instance, the domain model in Figure 3.2 could be derived into a class diagram by adding attributes and behaviors to objects, as shown in Figure 3.3.

In Figure 3.3, an autopipette's transfer() function realizes the behavior of transferring solution between containers, such as a Solution Container and a Beaker. A Solution Container object contains a Solution object, which represents the chemical solution stored in it. The Beaker also could own a Solution object. The Balance object is able to weigh the Beaker and the Bunsen Burner can heat the beaker.

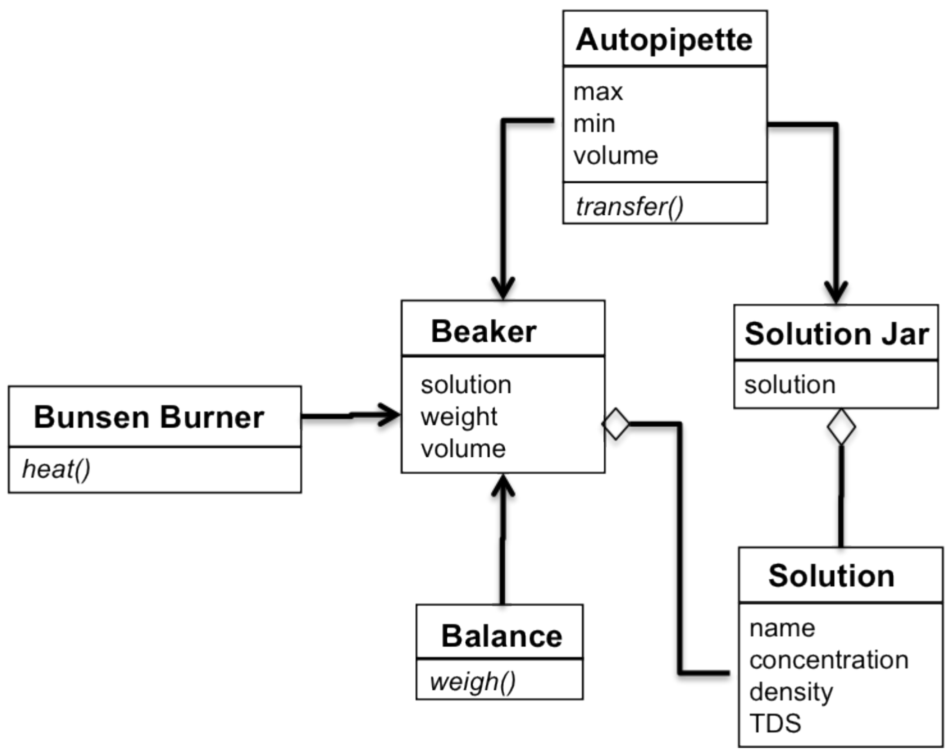

Figure 3.3: The class diagram derived from the domain model

In addition to the objects in the domain, the reactions between chemical solutions are modeled as rules. Each rule is composed of the information needed for a reaction, including reagents, catalyst, resulted chemicals, and reaction phenomenon (color, sound, smoke, precipitate, etc.). When there is a possible reaction detected (e.g. two different chemicals are put into a same container), these reaction rules will be checked. If a match is found, the matched rule provides information to change the status of related objects.

The domain model is independent of specific programming languages so one domain model can be implemented with any development tool with any programming language, which brings an important feature to the solution: it could support multiple concrete implementations of the same domain model. The potential consequence of this solution is that end-users are able to design a virtual world once and render it on different virtual world platforms.

3.1.2 User Interfaces

The basic elements of the domain-oriented language identified through domain modeling are presented to end-users through user interfaces. Designing user interfaces as a building tool that is similar to end-users' daily work environment could simplify the learning process of using this tool.

End-users interact with this domain-oriented environment through user interfaces, which decide how end-users organize the domain-oriented concepts according to their particular requirements. Those domain-oriented concepts could be presented to end-users textually or graphically. Considering that concepts in chemistry experimental education domain are visible and tangible real life objects rather than abstract and invisible concepts, showing them in a graphical manner could be intuitive and bring better perception of these objects.

In the domain of chemistry experimental education, chemistry educators work in a setting with lab benches and shelves holding chemistry instruments and chemicals. User interfaces that resemble this working environment would immerse end-users into a familiar surroundings to their daily work, and in turn shorten their learning time. The working environment of chemistry educators contains two major parts: an inventory with instruments and chemicals, and a lab bench upon which certain instruments and chemicals will be put for conducting chemistry experiments. The graphical user interfaces that reflect these two components may be more intuitive to chemistry educators and make learning easier.

3.2 Multi-Level Adaptation

As introduced at the beginning of this chapter, EUD suggests providing different levels of adaptation, from basic parameterization to complex modification, to end-users to fit their different requirements. The proposed solution considers this suggestion and incorporates this consideration into the design of the domain-oriented end-user development environment. This section explains how the domain-oriented end-user development environment has been designed to provide flexible adaptivity to end-users in three different levels: parameterization, integration, and extension.

3.2.1 Parameterization

Parameterization is the activity by which end-users control the attributes and behaviors of a portion of the software systems according to pre-defined choices provided by the systems. Parameterization, also known as customization, is commonly implemented in EUD environments (Buti et al., 2011; Lieberman et al., 2006; Repenning & Ioannidou, 2006b) tackling low level complexity. Section 3.1.1 abstracted basic building objects could be provided to end-users, such as the Beaker, the Balance and the Autopipette. The parameterization can be used to set parameters to change these basic objects' attributes. For example, the Beaker's weight or the Autopipette's minimum/maximum volumes should be flexibly set by end-users. Each solution's name and related chemical parameters like density are also configurable by values entered by end-users. This modification level gives end-users the simplest way to adapt the virtual chemistry experiments to their desired changes to the virtual experiments. For instance, end-users can simply change the solution name and density to change the result of the TDS experiment.

3.2.2 Integration

Integration allows end-users to compose basic building components together to form desired applications. In the case of virtual chemistry experiments, end-users should be able to choose required building components, which are chemical instruments, and put them together to form an experiment. For certain instruments like Containers, the components need to be combined with a Solution object to make the experiments workable.

3.2.3 Extension

With extension ability, end-users are able to further modify the applications they are using by adding new building components originally not existing in the applications. The building components of this proposed EUD tool are chemical instruments or chemicals that are represented by corresponding 3D models in the virtual worlds. However, the initial version of the EUD tool developed by computer science professionals could not provide all of the building components that their end-users will need in the future. Implementing extension ability for this EUD enables end-users to import new concepts and 3D models into the system to adapt their requirements.

3.3 Instantiation in Concrete 3D Virtual Worlds

Virtual world building tools provide users capabilities to set up virtual worlds, to build 3D objects inside virtual worlds and to enable interactions and animations for these objects. Some building tools are integrated within virtual worlds. For example, Second Life (http://secondlife.com) and Active Worlds (http://www.activeworlds.com) have their own build-in editors for adding new content for the virtual worlds. Other tools are development suites that are independent of any virtual worlds but are used to build virtual environments. Unity3D (http://www.unity3d.com) is a typical example. These two types of virtual world building tools share similar visual interfaces of 3D object creating and scripting or programming. These virtual world building tools are used for instantiating domain-oriented concepts in 3D virtual worlds.

The process of instantiating domain-oriented concepts in a 3D virtual world is the process of creating 3D objects with those concepts. For instance, the instantiation of the concept balance is to create a 3D object balance in a 3D virtual world using its building tool. The object building mechanism varies in different 3D virtual world building tools. In Second Life, primitives, which are basic solid shapes including cube, sphere, cone and cylinder, are used to build 3D objects. In Unity3D, 3D objects are built from meshes, a series of triangles forming the shape of 3D objects. Therefore for a 3D virtual world a library of pre-built 3D objects is created using its own 3D object building mechanism.

In addition to building of static 3D objects, the instantiation also involves the creation of the chemistry related attributes and behaviors on these objects, according to the domain model. For example, five 3D objects (beaker, balance, Bunsen burner, autopipette, solution jar with solution) were needed to instantiate the domain model designed in Section 3.1.1 in a concrete 3D virtual world. Scripting implements the dynamics of these 3D objects so that they interact with each other the way they do in the real world. Similar to the object building mechanism, different virtual world building tools provide different scripting languages for users to activate static 3D objects. Second Life has Linden Script Language (LSL) while Unity3D applies JavaScript and C#. Hence the instantiation of the domain model relies on underlying concrete virtual world platforms, while the domain model and domain-oriented user interfaces are virtual world platform independent.

3.4 Communication with Concrete Virtual Worlds

As mentioned at the beginning of Chapter 3, the domain-oriented environment interacts with end-users through domain-oriented user interfaces and communicates with underlying concrete virtual worlds through programming interfaces. While the end-user interfaces are uniform with the domain-specific language, the interfaces with different virtual worlds may be different in communication protocols and programming languages. Three important steps described below facilitate communication with concrete virtual worlds.

- Maintaining the configuration of virtual experiments built by end-users. An end-user builds a virtual experiment by combining required objects using the domain-oriented design environment. The configuration of these objects will be saved permanently by the design environment. The configuration information contains attributes like name, weight, volume, location in 3D space and dynamic behaviors such as the movement and rotation ability. Each virtual experiment is composed of a list of objects with configurations for that experiment, customized by the end-user and identified using a unique ID. A virtual world building tool renders the virtual experiment by retrieving the configuration information when it is informed with the unique ID.

- Sending building requests from the end-user design environment to the virtual world building tool to generate the virtual experiments. The building requests are sent through a communication protocol supported by a concrete virtual world building tool. A daemon service waits for requests and handles them when they arrive. A request carries the unique ID mapping to a virtual experiment configuration that is permanently stored somewhere else. The virtual world building tool retrieves the configuration of the virtual experiment and renders it.
- Returning the building result. The virtual world building tool returns the result of generating the required virtual experiment to the domain-oriented design environment so that end-users could be notified with the access to the virtual experiment if they are built successfully or with errors if the building processes are failed.

This communication process described above can be applied for any virtual world building tool with external interfaces for communicating with other systems. The difference is how each virtual world building tool implements these three steps. This dissertation will present one implementation of a concrete virtual world building tool in the next chapter.

3.5 Summary

This chapter introduces a domain-oriented end-user design environment as a solution to the problem identified in previous chapters. Four major concerns related to the design and implementation of such a system, which are domain modeling, user interfaces design, instantiation in and communication with concrete virtual world platforms, are discussed in this chapter. The next chapter will illustrate the implementation of the solution as a prototype *iVirtualWorld*, focusing on the user interface implementation, domain-oriented concept instantiation in one virtual world platform and communication to that virtual world platform.

4. Implementation of *iVirtualWorld*

Chapter 3 introduced the design of a domain-oriented end-user development environment for building 3D virtual chemistry experiments. A domain model was designed and several design concerns were addressed. The design of the solution is generic and does not rely on a specific virtual world platform, which implies that the implementations could be various. With this solution, software developers are free to choose user interface development tools and virtual world platforms as long as they could address the considerations discussed in Chapter 3. The author first partially implemented the solution in a simple domain, virtual presentations, for an early evaluation. The development of the initial prototype, named *iVirtualWorld*, focused on implementing the graphical user interfaces, multi-level adaptation, instantiation of 3D learning environments in different virtual world platforms and communication to different virtual world platforms. The work then has been extended to the domain of chemistry and biology experimental education by realizing the domain model in a concrete virtual world platform Unity3D. This chapter first introduces the implementation of *iVirtualWorld* in the virtual presentation domain (Liu, Zhong, Ozercan, & Zhu, 2013). Then the implementation details of the domain-oriented end-user development environment are presented, including user interfaces, multi-level adaptation, instantiation in and communication with the concrete virtual world platform Unity3D.

4.1 Virtual Presentations

Based on the design introduced in the chapter 3, *iVirtualWorld* works as an agent linking end users and different virtual world building tools. On one end, *iVirtualWorld* supplies domain-oriented interfaces to end users to help them build virtual worlds. On the other end, it communicates with different virtual world building tools with end users' requirements and launches the building processes on these tools. The prototype for the virtual presentations implemented template-based graphical user interfaces for end-users to adapt the content presented in 3D virtual environments to their needs. The instantiation of templates of 3D learning environments in different virtual world platforms is wrapped by *iVirtualWorld* and is transparent to end-users.

4.1.1 User Interfaces Design

A set of similarly functional virtual environments is abstracted as a virtual world template. For each template, platform-dependent 3D models have been pre-built according to the template structure. *iVirtualWorld* presents virtual world abstraction and interfaces to end users in a visual manner using web pages. Figure 4.1 shows a virtual world template and its interfaces using this visual manner. The left part displays the floor plan of this virtual world template and indicates ten content attributes, numbered from 1 to 10. Each number on the floor plan represents a placeholder where end-users can put their own content. The right part is the place where end users assign actual contents to these placeholders, in which *Content_1* through *Content_8* have been linked to images. Each placeholder only accepts content with the type specified on that place. For example, number 8 placeholder can only host a video. The placeholders with type image(s) are designed to accept either a single image or a slideshow. This implementation combined parameterization and extension so that end-users can make decisions based on pre-defined choices (e.g. decide whether to use an image(s) placeholder for an image or a slides show) and add new content to the system (e.g. upload a new slides show).

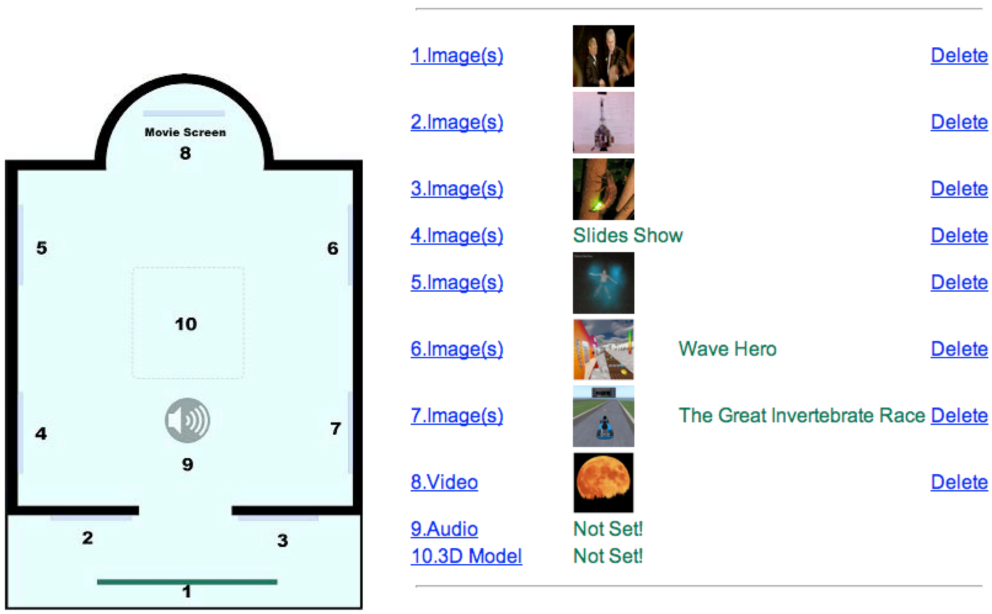

Figure 4.1: The abstraction of a type of virtual worlds and its interfaces in *iVirtualWorld*

iVirtualWorld has been developed as a web application providing platform irrelevant authoring interfaces for end users creating virtual world applications. Information obtained from the process of building virtual worlds is stored in a database. The design of virtual worlds is not tied to an underlying platform. A virtual world is rendered only when an end user specifies a virtual world platform supported by *iVirtualWorld*. Otherwise, virtual worlds are represented abstractly by database records, which can be retrieved and modified. A virtual world can be instantiated in different virtual world platforms. *iVirtualWorld* supports Unity3D and OpenSim (http://www.opensimulator.org) currently.

iVirtualWorld also implements a step-by-step wizard that directs end users to create virtual presentations by walking through a sequence of related web pages with necessary configurations. No scripting activities are required during the building of virtual worlds.

4.1.2 Instantiation in Concrete 3D Virtual Worlds

Pre-defined virtual world templates are created and mapped into OpenSim and Unity3D objects respectively. Templates for OpenSim are constructed using building tools integrated in OpenSim, while templates for Unity3D are created using Unity3D Editor or by importing 3D models from third-party 3D modeling tools such as Blender and Maya. Objects in OpenSim are encapsulated using OpenSim scripts and Unity3D objects are packaged using Unity3D scripts. All objects mapped to the same abstract object in *iVirtualWorld* expose an identical interface to end users through the abstract representation no matter which underlying virtual world platform will be used eventually. This feature enables future extension of *iVirtualWorld* to other virtual world platforms without changing user-defined virtual world applications.

4.1.3 Communication with Concrete Virtual Worlds

Communication between *iVirtualWorld* and Unity3D is implemented using socket programming under TCP/IP communication protocol. A socket server is developed as a daemon process and deployed on a server on which Unity3D is installed. This socket server listens to a specific port. Once it receives a valid request, it interprets this request and launches Unity3D to compile the Unity3D project. The socket client is installed on the HTTP server where the *iVirtualWorld* website is deployed. When an end user requires a building activity, corresponding PHP codes invoke this socket client, and send a request to the socket server.

Communication between *iVirtualWorld* and OpenSim works differently. The *iVirtualWorld* website incorporates an OpenSim PHP wrapper file that encapsulates the low-level communication. Building requests are sent to the OpenSim server after instantiating an object and calling functions defined in this PHP file with parameters submitted by end users.

4.2 Implementation of Domain-Oriented Design in Unity3D

The successful development of the solution in the virtual presentation domain confirmed a part of the design towards an end-user development tool for building 3D virtual educational environments. The goal of the current design is to build 3D virtual chemistry experiments, so the prototype needs to be extended to implement the domain-oriented design described in chapter 3. Unity3D has been selected as the first virtual world platform to instantiate the domain model and to realize the virtual chemistry experiments.

Unity3D is a powerful development suite that can be used to build 2D/3D simulations, games, and virtual worlds. Unity3D features publishing projects as Windows/MacOS standalone applications, web applications and mobile applications for iOS and Android devices. The author chose Unity3D as the concrete virtual world platform of the solution. To instantiate the domain-oriented concepts in Unity3D, a Unity3D project was created beforehand, with a pre-built virtual lab room and lab benches. Once an end-user assembles a virtual experiment through the domain-oriented user interfaces of *iVirtualWorld*, this Unity3D project is compiled with configurations containing all of the 3D objects selected by the end-user and is published as a web application. All of these 3D objects can be operated according to the attributes and behaviors configured in the graphical user interfaces of *iVirtualWorld*. Instantiation in Unity3D involves two stages of work. At the first stage, 3D objects are created and can be loaded into the Unity3D project. At the second stage, these 3D objects need to be manipulated using programming.

4.2.1 Instantiation of 3D Objects in Unity3D

Because the domain-oriented development environment enables end-users to choose what objects will present in the virtual experiments, the system developers would not know in advance what objects should be rendered in the virtual experiments. There is a need to dynamically load 3D objects into the Unity3D project according to end-users' choices. Unity3D can dynamically load 3D objects in a format called Asset Bundles deployed on a web server. The limitation is that the 3D objects have to be built by developers in Unity3D and then to be exported as Asset Bundles to the web server. The process is time-consuming. There are free 3D objects resources on the Internet such as Google 3D Warehouse, which is a platform for sharing 3D objects in Google SketchUp (*.skp) format. Utilizing these free resources have two advantages: 1) It saves efforts on building 3D objects which in turn prevents "reinventing the wheel"; 2) It has the potential to enable *iVirtualWorld* end-users to enrich the object library through searching for objects by themselves, uploading them to *iVirtualWorld*, using them and sharing them with other end-users. A third-party open source plug-in of Unity3D (Drozdz, 2010) implements the dynamical loading of 3D objects in a format (OBJ files) designed by Wavefront Technologies, which is an open format that is supported by many 3D modeling applications or can be converted from other formats. Non-OBJ files can be converted to OBJ files to be loaded. Figure 4.2 displays a pipeline to convert Google SketchUp files to OBJ files. Three-dimensional objects are downloaded from the Google 3D Warehouse as **.skp* files. These *.skp files can be imported to the Google SketchUp free version and be exported as *.dae files. Then the *.dae files are converted to *.fbx files through the Autodesk FBX Convertor. Lastly, *.obj files are created from *.fbx files also using the Autodesk FBX Convertor. With the combination of the pipeline and the Unity3D plug-in, 3D objects can be obtained from the Google 3D Warehouse and be converted into *.obj files, which will be dynamically loaded at runtime.

4.2.2 Manipulation of 3D Objects in Unity3D

In a virtual chemistry experiment, students should be able to interact with 3D objects, including picking up an instrument, moving or rotating it, and observing the change of chemicals. Developers activate 3D objects in Unity3D by attaching attributes and behaviors scripts to them. Unity3D scripting incorporates two popular programming languages, JavaScript and C#, instead of creating another new scripting language. Therefore, computer science professionals with JavaScript or C# knowledge can easily use Unity3D. The author chose JavaScript as the major language for instantiating and activating 3D objects because of the prior experience, although no significant performance difference exists between using JavaScript and C# in Unity3D.

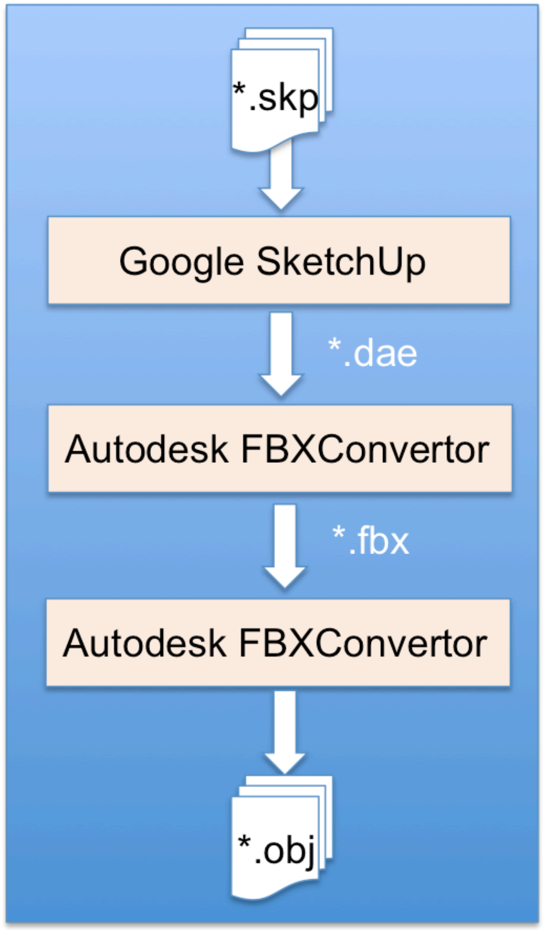

Figure 4.2: The pipeline of converting *.skp files to *.obj files

The sample domain model designed in Section 3.1.1 directs the developers to implement the scripting of 3D objects. In order to convert the domain model into source codes in a concrete virtual world platform, further refinement using object-oriented software design and development technologies is needed. Since most of the chemistry instruments and chemicals share common features such as temperature, weight (or mass) and volume, a parent class *IvwObject* is abstracted, inherited by almost all of the instruments and chemicals except for the Autopipette and the Balance classes. The weights, temperatures and volumes of autopipettes and balances are usually not measured in chemistry experiments. Figure 4.3 illustrates the hierarchical, association and aggregation relationships among the classes designed for *iVirtualWorld*. Notice that more objects (Dish, Testtube, Electric hot plate, etc.) have been identified from the chemistry laboratory manual used for domain modeling. Although these objects were not presented in the sample domain model in Section 3.1.1, they have the same role of the Beaker or the Bunsen Burner in the sample domain model. Considering that Bunsen Burner is one heating source and there may be different heating sources used in chemistry experiments, it is reasonable to abstract a parent class for different heating sources. Figure 4.3 added a class Heating source with Bunsen Burner, Electric Hot Plate and Alcohol Burner as its children classes. Figure 4.4 shows a segment of the script for the Heating source and its visual effect when using on a Bunsen burner object.

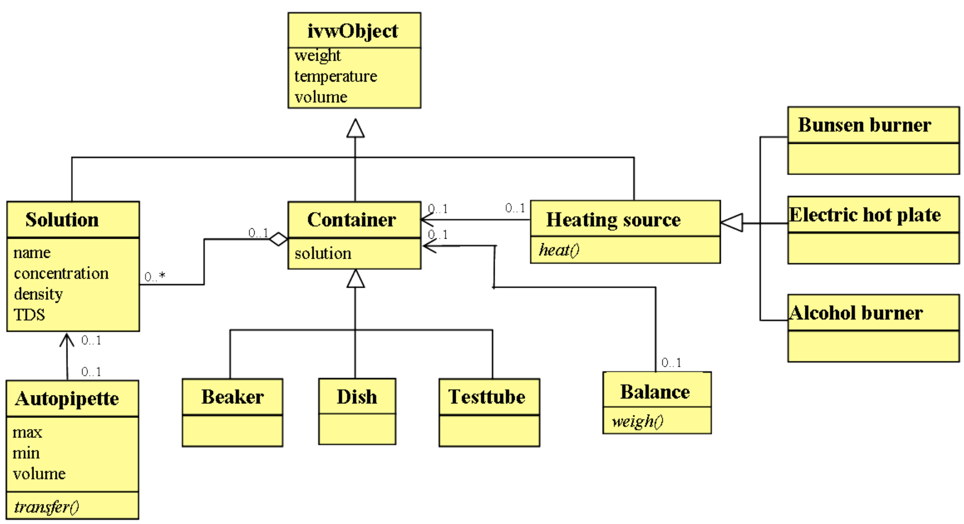

Figure 4.3: The class diagram of *iVirtualWorld*

Moving and rotating 3D objects are basic operations and are important in the implementation of the virtual experiments because manipulating objects are in almost all experiments. The movement of 3D objects in *iVirtualWorld* is implemented as following: the virtual experiment players move an object by pressing the left mouse button on this object and move the mouse to move the object along the horizontal plane. The vertical movement is implemented by scrolling the mouse wheel up and down. The system detects the mouse events and reads in the mouse displacement at three dimensions, which is converted into the movement of the object at three dimensions in the virtual world. The rotation is controlled by pressing one key on the keyboard to modify the rotation angle of the object at one dimension. The movement and rotation operations are written in individual JavaScript files for reuse.

(a)

```
#pragma strict       // Enforce the static typing

class HeatingSource extends IvwObject {
    var obj4Heat : GameObject;       // The object to be heated
    private var flag;                // true-on; false-off;

    function Init() {
        flag = false;    // The heating source is initially off
        ...
    }

    function Update() {
        if (Input.GetButtonDown ("Fire1"))  // This is the mechanism
        {                                   // of Unity to detect
            ...                             // left-click event
            Heat();                         // calling Heat() function
        }
    }

    function Heat () {
        ...                                 //The code to heat the object
    }
}
```

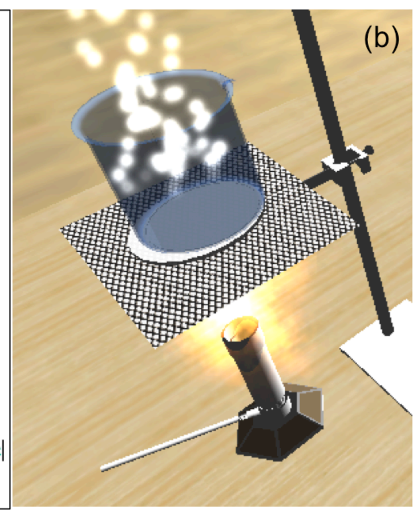

Figure 4.4: The Unity3D JavaScript code segment of the Bunsen burner and the visual effects in virtual experiments

In addition to common operations such as moving and rotating objects, some objects need special manipulations. For example, the virtual experiment players may need to control an autopipette object to retrieve or release the solution. The heating source object should be turned on/off by clicking on it. Figure 4.4 (a) shows a segment of the source code for the heating source. When the heating source object is clicked, the heat() function will be called to turn on the heating source and start heating any object on top of it. Figure 4.4 (b) displays the effect of the Bunsen burner as a heating source with a flame animation in the virtual experiment.

Unity3D provides a collision detection mechanism to detect the interactions between objects. Collision detection generates collision events and passes the events to callback functions defined in objects involved in this collision. The event callback functions are the entrance for handling the interaction between objects. Figure 4.5 briefly shows the structure of a collision detection callback function's structure. For instance, to weigh a beaker, the players move the beaker towards a balance. When the beaker touches the balance surface, Unity3D collision detection creates an event and notifies the beaker object's collision callback function. The callback function inside the Beaker class displays the weight attribute value on the screen.

```
function OnControllerColliderHit (collision : ControllerColliderHit) {
	// the collision event was passed into this callback function
	// the collided object can be retrieved from the event object
	var collidObjectName = collision.gameObject.name;
	… // source codes handling the collision event
}
```

Figure 4.5: The Unity3D JavaScript code segment of the collision detection

JavaScript files related to the attributes and behaviors of 3D objects will be attached to the corresponding 3D objects when Unity3D loads virtual experiments at the beginning of run-time. When players interact with the virtual experiments, the attached JavaScript source codes are invoked. .

The chemical reaction rules are stored in MySQL database for persistence and are loaded when a virtual experiment is launching. Some events could initiate scripts to search these rules and change object statuses according to the result. For example, in a virtual experiment students use the autopipette to transfer chemical A into a container that has chemical B in it, the system invokes scripts to search on the reaction rules to see if there exists a reaction between chemicals A and B. If a reaction is found, the system changes the status of those involved according to the reaction results.

4.2.3 Graphical User Interfaces

iVirtualWorld domain-oriented end-user design interfaces were implemented as a web application providing features such as cross-platforms, non-installation needed, central computing, and flexibility of access. As discussed in Section 3.1.2, the goal is to simulate the working environments of chemistry experimental educators by graphically presenting a lab bench and an inventory with domain-oriented concepts identified in the domain model. The inventory is displayed to end-users with a 2D icon for each instrument or chemical as shown on the left side of Figure 4.6. Textual labels for the instruments are also given to better inform end-users. A 2D image of a lab bench is shown to indicate that space above is the workspace of the lab bench. Virtual items on the lab bench are visualized in the workspace as shown on the center of Figure 4.6. The workspace presents a top view of the lab bench and indicates end-users of the position of each instrument or chemical on the bench. The attributes and behaviors of each instrument or chemical could be configured using the setting tab displayed on the right side of Figure 4.6.

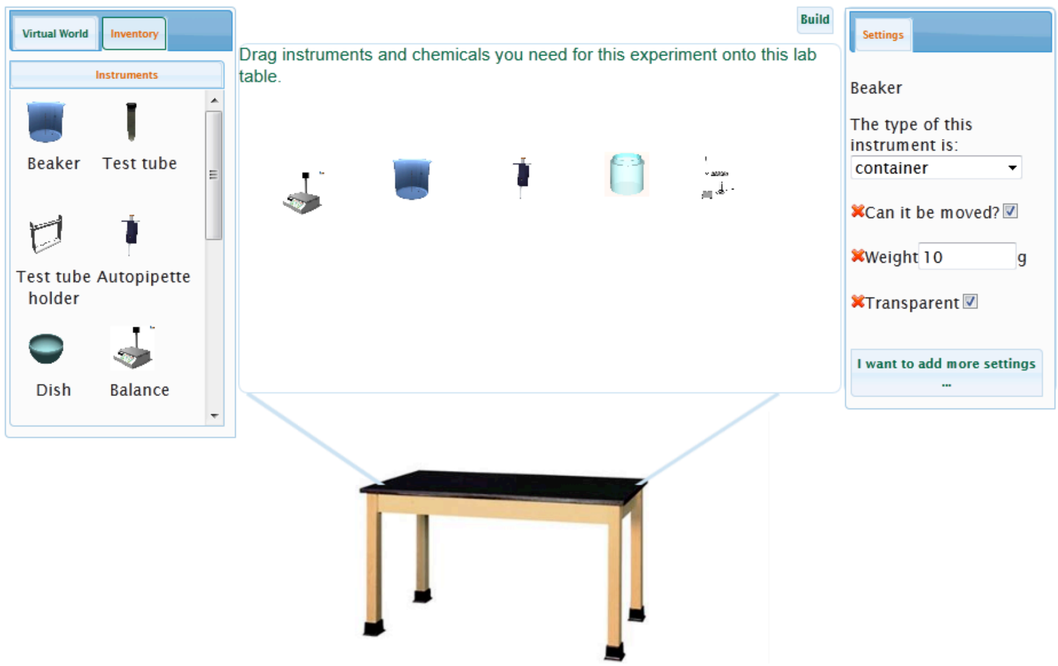

Figure 4.6: *iVirtualWorld* graphical domain-oriented end-user interfaces with the inventory of domain concepts (left), the virtual lab bench (center) and the settings of attributes and behaviors (right)

In addition to traditional web graphical user interface elements such as icons and images, recent dynamic web technologies enable more complicated interactions including drag-and-drop using client-side scripting. The process of the drag-and-drop can be considered as an analogy of the process of preparing a real world chemistry experiment. In the real world, chemistry educators grab instruments and chemicals and put them on the lab bench. Using the domain-oriented end-user design interfaces, educators select an instrument from the inventory (As shown in the left of Figure 4.6), drag it to the lab bench and drop it on the workspace (the center of Figure 4.6). End-users can also arrange items that are already on the bench by moving them to change their positions. End-users can configure an instrument by clicking on the icon on the workspace to bring out the settings tab (the right of Figure 4.6). In Figure 4.6 the beaker object was clicked and the beaker's settings are shown on the right side. End-users can decide whether their students can move the beaker in the virtual experiment by setting the value of the "*Can it be moved around by users?*" checkbox. If the checkbox is checked, students can move the beaker in the virtual experiment. End-users can also set the beaker's weight to different numbers according to their requirements.

The configuration of a virtual experiment is stored in a MySQL database for persistence. The information is retrieved when end-users need to modify the virtual experiment settings or to build a virtual experiment.

4.3 Multi-Level Adaptation

Section 3.2 introduced the design of the adaptivity of the domain-oriented end-user development environment in three levels: parameterization, integration, and extension. This section illustrates how these different levels are implemented in the prototype *iVirtualWorld*. The implementation of the multi-level adaptation has been completed in two phases. In phase one, the parameterization and integration were developed and evaluated. The extension ability was incorporated during phase two.

4.3.1 Parameterization

As introduced in Section 3.2.1, the parameterization is the activity that end-users control the attributes and behaviors of individual objects by making decisions on pre-defined choices. Based on the domain-oriented design, choices of different attributes and behaviors of those objects should also be domain-oriented, i.e. be presented using the domain-oriented language. Take a Beaker object as an example, the attributes could be the weight and the volume, and the behaviors could be more dynamic like whether this object can be moved or rotated in the virtual experiments. *iVirtualWorld* provides interfaces accepting end-users' decisions on these attributes and behaviors. The results of the parameterization are stored in the database. When a virtual experiment is launched, it reads configurations from the database and loads objects with attributes and behaviors decided by the configurations.

When an end-user is designing an experiment, such as the TDS experiment introduced in Section 3.1.1, he/she needs to specify one solution and set the attributes of this solution using parameter settings shown in Figure 4.7. The end-user has the freedom to choose appropriate parameters for this solution to yield different experiment results for his/her students.

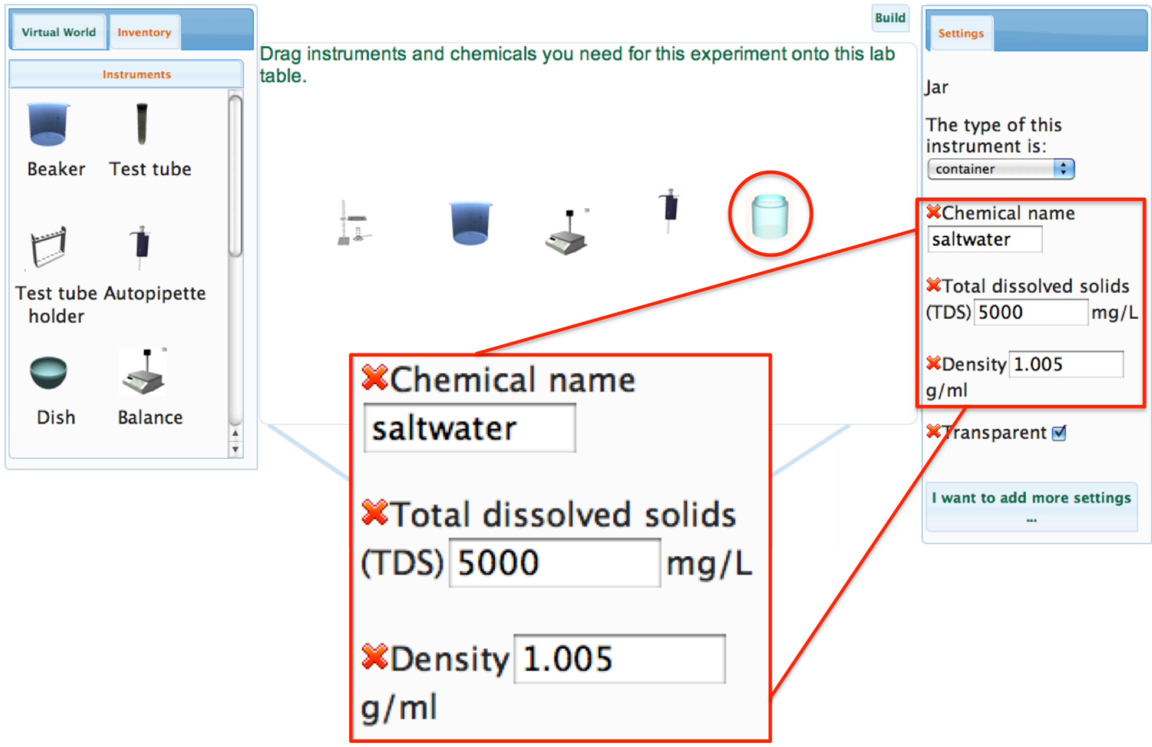

Figure 4.7: Parameterization of an instrument in a virtual chemistry experiment

4.3.2 Integration

Integration allows end-users to compose a virtual experiment scenario by gathering individual objects together. For end-users, integration means choosing required objects from the inventory, putting them onto the lab bench, and setting attributes and behaviors for them. It is an adaptation level further than parameterization. The implementation of integration in Unity3D is more complicated than that of the parameterization since it involves the interaction between objects. End-users compose individual objects to form a virtual experiment, in which their students can manipulate those objects following experiment procedures. These procedures usually are composed of the interactions between more than one object. For instance, to transfer the solution between containers, the autopipette needs to be moved to interact with containers. This procedure contains moving an autopipette towards a container and inserting the autopipette tip in the container and the player presses the space bar. The autopipette object will release the solution into the colliding container. Figure 4.8 illustrates the code segment of the interaction between an autopipette and a container. The interaction will be detected so that the virtual experiment can prompt students to retrieve or release the solution using the autopipette.

Unity3D Collision detection mechanism is employed in *iVirtualWorld* to process the interaction between objects. Collision detection detects the physical interaction between two objects, generates collision event with the necessary information, and notify the collision detection callback functions in the objects that are involved in the collision. These callback functions are the entrance points to process the interaction. For example, when students weigh a beaker using a balance, the beaker is moved on top of the balance surface. Collision detection of Unity3D creates an event and notifies the beaker object. Beaker object's callback function reads its weigh property and displays the number on the screen. In the solution-transferring example, when an empty autopipette collides with one container filled with solution and students press the space bar, the event with the container's name is sent to the callback function. The callback function tracks back to the container object, retrieves its solution name and fills the same solution to the autopipette object with the amount set by the retrieval volume. Later when the autopipette collides with another container and the students press the space bar, the autopipette object releases the solution into the colliding container.

Large portions of chemistry experiments are about the chemical reaction. When two different solution objects interact with each other, they may produce a reaction. Reaction rules are maintained in a MySQL database table. When a virtual experiment launches, it loads in these rules and keeps them in the memory. When there is a collision of two different solutions, the reaction rules are searched. If there is a match, the virtual experiment reads the reaction information and makes changes to objects involved according to the results.

4.3.3 Extension

The parameterization and the integration bring certain adaptivity of software applications to end-users, based on pre-defined and already existing content. However, software developers cannot predict future requirement changes and it is almost impossible to provide a complete library of content to end-users to fit their requirement change. The extension is a further adaptivity to exceed the limitation by enabling end-users to introduce new content that previously does not exist in the application. *iVirtualWorld* implemented this level of adaptation to allow end-users to incorporate new chemical instruments by using the technology introduced in Section 4.2.1.

A conversion service is developed as a socket server accepting requests for converting *.skp files to *.obj files. Following the pipeline described in Figure 4.2 in Section 4.2.1, the conversion service calls Google SketchUp and Autodesk FBX Convertor to implement the task. The conversion is developed as an automatic process without human interaction based on a capability of Google SketchUp and Autodesk FBX Convertor that these two programs can be operated through command lines commands.

In addition, Google SketchUp supports Ruby scripts to manipulate 3D models without opening the Google SketchUp GUI. This feature of Google SketchUp enables certain pre-conversion adjustments on 3D models to fit them better in *iVirtualWorld*. For example, the sizes of 3D objects downloaded from Google Warehouse are various. If these 3D objects are imported into *iVirtualWorld* without any adjustments, they can be as big as the whole laboratory room or too small to be visible. A Ruby script has been developed to confine the size of 3D models to an appropriate setting so that these models can be displayed in the virtual worlds in an appropriate proportion to the environment. The script also translates 3D models to make sure they are centered at the origin point and captures a thumbnail image that is used by the "inventory" list on the *iVirtualWorld* webpage. Figure 4.8 illustrates how a Google Warehouse 3D model can be imported into *iVirtualWorld* by an end-user.

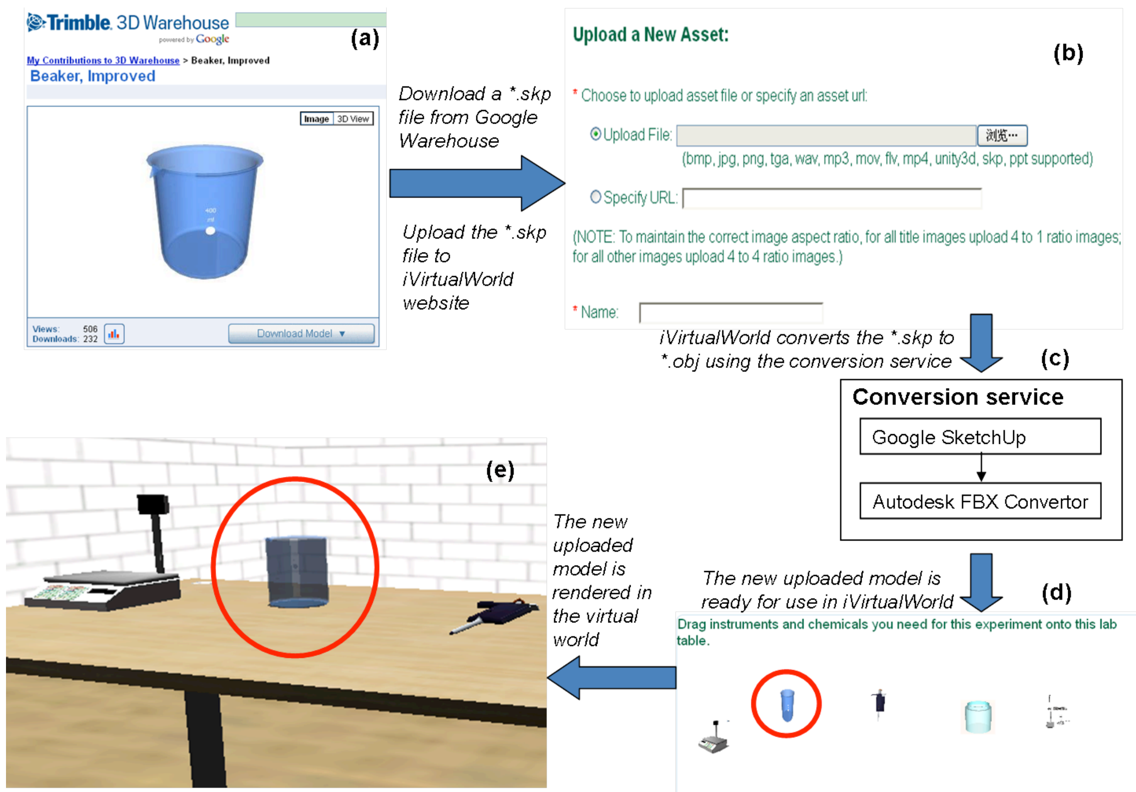

Figure 4.8: The extension feature of *iVirtualWorld*. (a) A 3D model on Google Warehouse website is downloaded as a *.skp file. (b) The *.skp file is uploaded to *iVirtualWorld* through the upload webpage. (c) The *.skp file is converted to a *.obj file by the Conversion Service. (d) The new imported model is available for this end-user to use. (e) The new imported model is rendered in the virtual experiment.

A 3D model from Google Warehouse and gone through the conversion service will be loaded into the 3D virtual experiments and be attached with the JavaScript IvwObject.js, which is the root class and the default script for new added 3D model. So far this 3D model is a static 3D object. More specifically, this 3D model would not have any dynamic property and the players of the virtual experiments could not manipulate it. For example, the players could neither move it nor rotate it. This 3D model would not interact with other 3D models either.

The parameterization with a list of pre-defined attributes and behaviors is applied to activate static 3D models. When a new 3D model is just imported, there is no attribute or behavior assigned to it. End-users need to select proper attributes or behaviors from the list shown in Figure 4.9. Once attributes or behaviors are assigned to the 3D model, end-users set appropriate parameters to these settings and hence activate this 3D model.

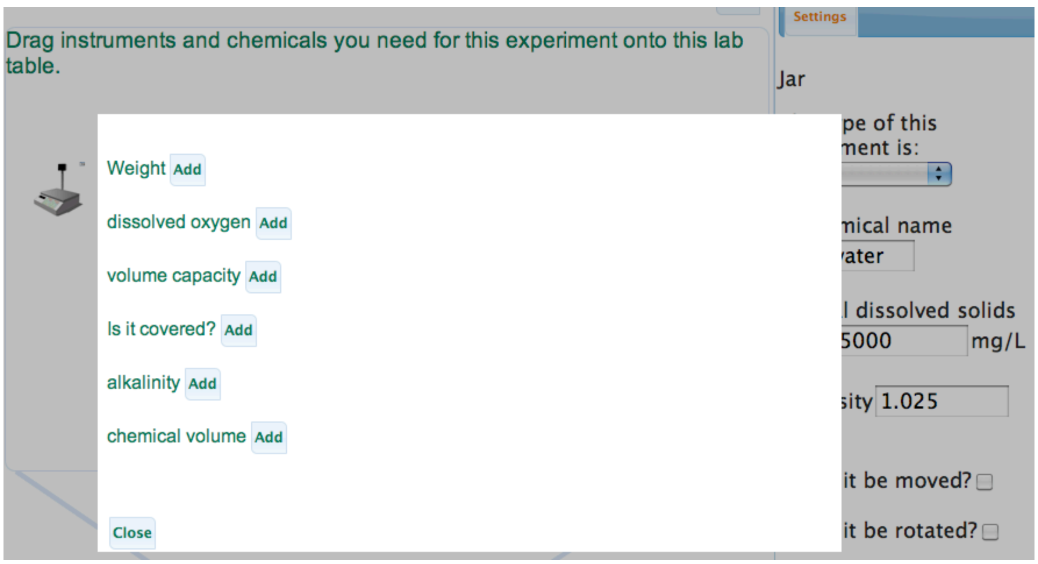

Figure 4.9: The attributes and behaviors list for 3D models

Each item in the attributes and behaviors list connects to either a variable in the object class attached to a 3D model or a JavaScript file. For example, the "Weight" attribute is mapped to the weight variable in *IvwObject,* while the "Can it be moved?" behavior is implemented in a separate JavaScript file that is attached to those 3D models with this feature checked.

Some interactions between objects in the virtual experiments happen not only on one single object but also on all of the objects sharing the same type. For example, the autopipette can be used to retrieve solution from or release solution to not only just a beaker but also other objects with the type container. A beaker with solution can be heated on not only the Bunsen Burner but also on other heating source. *iVirtualWorld* summarizes several common types with attributes and behaviors shared by the objects with the same type. Pre-defined objects have been assigned types according to their natures. However, new imported 3D models have no type assigned when the conversion completes. End-users should know the type of the new added 3D model and *iVirtualWorld* enables them to set the appropriate type to it. Figure 4.10 demonstrates the type listing for 3D objects. Each type name maps to a type class and when a type is assigned to an object, the system attaches the JavaScript file of the associated class to that object. The type "other" is mapped to the *IvwObject* class.

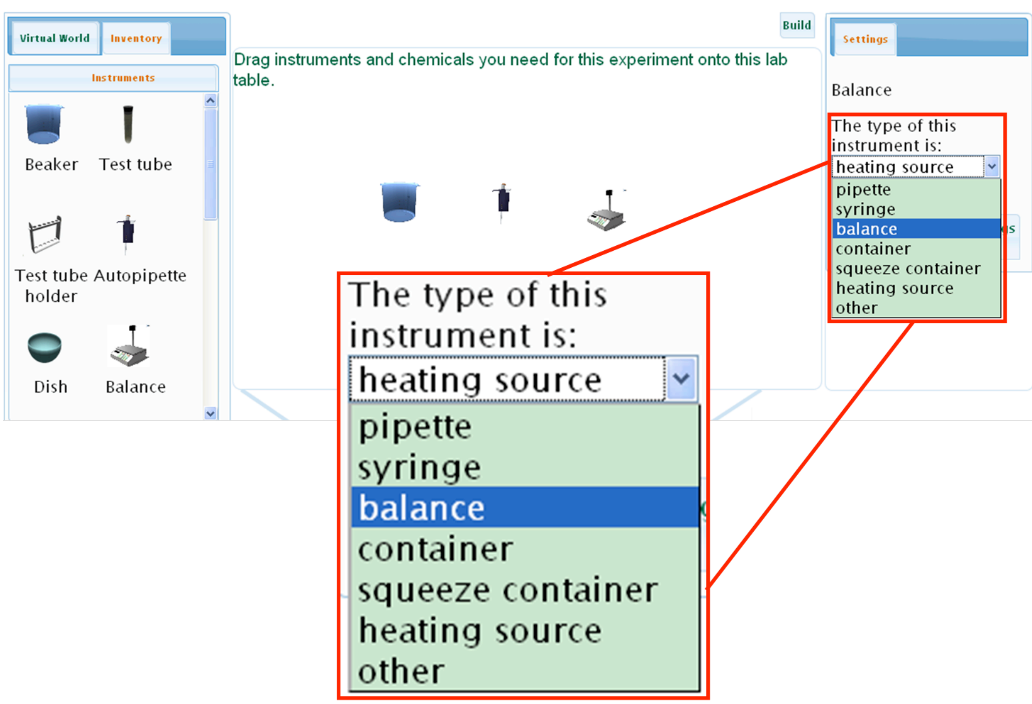

Figure 4.10: The type selection for new imported 3D models

4.4 Communication with Unity3D

The communication between *iVirtualWorld* and concrete virtual world building tools was designed in Section 3.4 as three steps. This section describes how these three steps work between *iVirtualWorld* and Unity3D.

First, *iVirtualWorld* saves the configuration information of a virtual experiment in MySQL database. A table stores basic information of a virtual experiment such as the name, the description and the creation date. The unique primary key maps to multiple records in another database table that saves the configuration of objects chosen by end-users for this virtual experiment. There is a one-to-many relationship between these two tables. When an end-user finishes composing a virtual experiment, *iVirtualWorld* forms an XML file using the configuration information and save it on the HTTP server for Unity3D to render the virtual experiment later. Appendix C An XML File shows an XML file of a virtual TDS experiment.

In the second step, *iVirtualWorld* web application communicates with Unity3D by TCP/IP communication protocol. As Figure 4.11 illustrates, a socket client is built in the web server. When there is a request to build a virtual experiment, the *iVirtualWorld* web application calls the socket client to send the request, containing the unique ID of the virtual experiment, to the socket server built in the Unity3D server. The socket server receives the request and launches Unity3D to compile the virtual experiment project and publish the project as a web application.

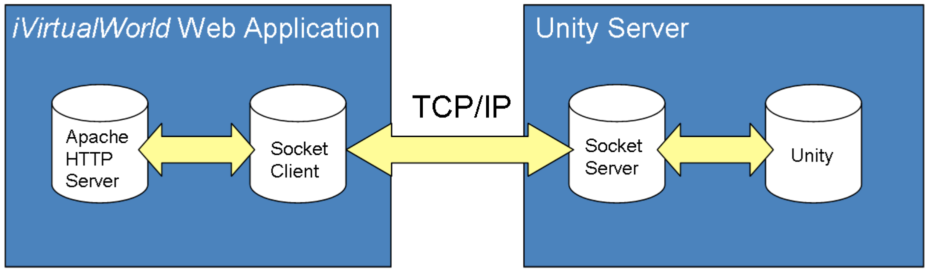

Figure 4.11: The communication with Unity3D

At last, when the Unity3D project is successfully compiled and published, the result is returned from the socket server to the socket client, notifying the end-users with the URL of the virtual experiment. If the compilation is failed, the socket server returns possible reasons causing the failure to the socket client, and in turn notifies end-users.

4.5 An Example of *iVirtualWorld* Application

Previous sections described the implementation of *iVirtualWorld* in discrete components separately. A simple but complete example can help explain how these components of *iVirtualWorld* works as a whole. Figure 4.12 illustrates how a domain concept is converted into a concrete 3D virtual world object by *iVirtualWorld*. A teacher identifies a domain concept beaker from the inventory displayed in Figure 4.12 (a) and drags its visual representation, i.e. the icon, onto the lab bench top in Figure 4.12 (b). The teacher then sets the attributes and the behaviors of the beaker, as shown in Figure 4.12 (c). At last, the beaker with its attributes and behaviors are instantiated in a concrete virtual world platform presented in Figure 4.12 (d). If the beaker's weight property is set to 10 grams by the teacher, in the virtual experiment the balance reading is 10 g when students move the beaker onto the balance.

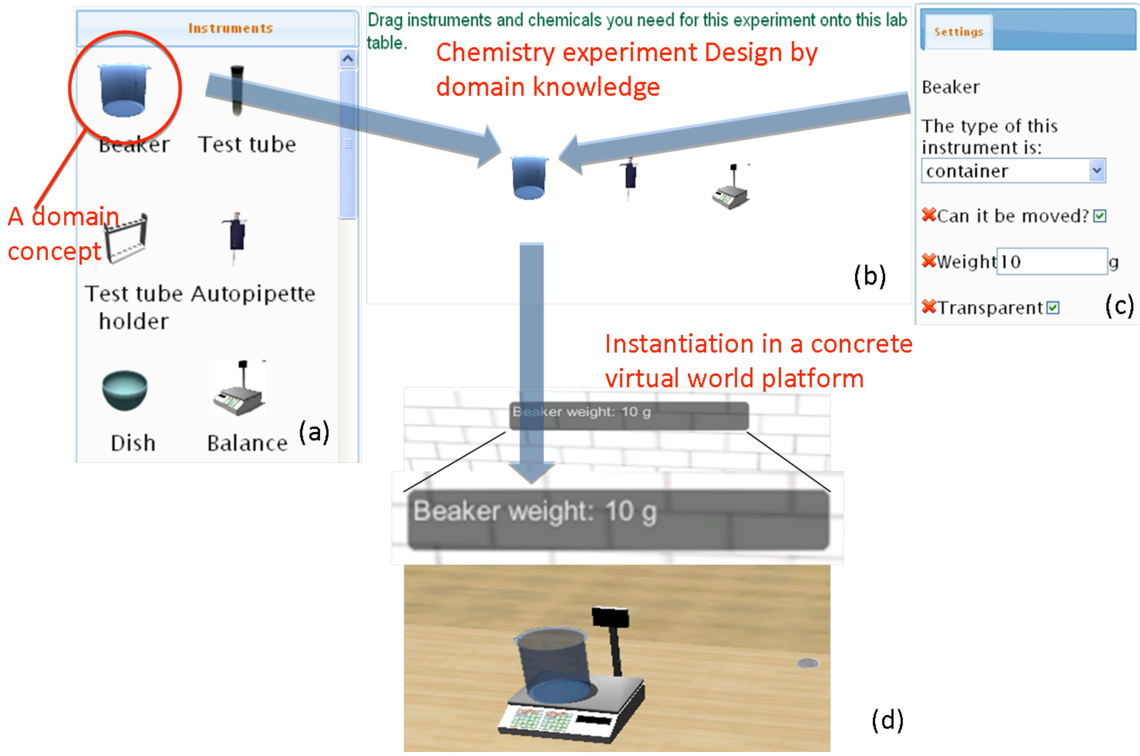

Figure 4.12: An example showing how *iVirtualWorld* converts a domain concept to a concrete 3D virtual world object. (a) Visual representations of domain concepts (b) Visual representation of lab bench top (c) Attributes and behaviors of a selected domain concept (d) The instantiation of the domain concept in a concrete virtual world platform

4.6 Outcomes and Limitations

The development of the prototype *iVirtualWorld* implemented ten basic chemistry instruments: beaker, test tube, test tube holder, autopipette, dish, balance, Bunsen burner, solution jar, syringe, and bottle. Google Warehouse provides numerous 3D models that can be imported into *iVirtualWorld* as additional instruments or other objects. Seven types of objects are supported by *iVirtualWorld* so far: pipette, syringe, balance, container, squeeze container, heating source, and other. Four basic operations (weighing by a balance, heating using a Bunsen burner, transferring chemicals by an autopipette, and titrating with a syringe) can be combined to form different experiments. Twelve properties facilitate the parameterization. The experiment examples include TDS and Dissolved Oxygen (DO) with six chemical reaction rules.

The current solution has limitations. The design and development of the solution was to explore the application of EUD technologies, specifically domain-modeling, domain-oriented user interfaces, and multi-level adaptation, in the virtual chemistry experiment domain. The purpose was to provide a paradigm of such a solution and to evaluate the effectiveness of this solution. This dissertation does not aim at a comprehensive development tool for end-users to generate arbitrary virtual chemistry experiments, although the current solution can be extended by the domain developers by expanding the domain model. For example, the current implementation focuses on chemicals as solutions, but developers can incorporate another class "gas" to the classes diagram by inheriting the *IvwObject* root class, which brings chemicals in the gas status to the system. The developers then need to realize the gas class in Unity3D for its unique attributes and behaviors other than those in the *IvwObject* class. Moreover, with the platform-independent design of the solution, developers who are interested in this domain can even instantiate the virtual chemistry experiments using other concrete 3D virtual worlds.

4.7 Summary

After presenting the implementation of a prototype, *iVirtualWorld*, in the virtual presentation domain, this chapter described how *iVirtualWorld* was extended to the chemistry experimental education domain. Major implementation issues were discussed including the instantiation of domain-oriented concepts in a concrete virtual world platform Unity3D, the user interfaces development, the multi-level modification mechanism, and communication between the *iVirtualWorld* web application and Unity3D. The *iVirtualWorld* user interfaces were developed as a web application, with graphical presentations of domain-oriented concepts as basic building blocks. The instantiation of domain-oriented concepts in Unity3D platform involves 3D objects building and scripting. Three levels of modification were implemented to provide end-users a "gentle slope" (Lieberman et al., 2006) to adapt the system according to their requirement changes. The configuration information of a virtual experiment is saved in a MySQL database, which can be retrieved by *iVirtualWorld* when building the virtual experiment. *iVirtualWorld* web application sends building requests to the Unity3D server and receives building results through the TCP/IP protocol.

5. Evaluation

Previous chapters discussed the technical difficulties chemistry educators face when applying 3D virtual world technologies in experimental education. A domain-oriented end-user development environment was proposed for users in the domain of chemistry education to build their own 3D virtual chemistry experiments without knowing 3D modeling and programming skills. An initial work, *iVirtualWorld*, partially implemented the proposed solution in the virtual presentation domain for early evaluation. Then *iVirtualWorld* was extended to full realization of the solution in two main phases. The first phase built the framework containing Chemistry domain-oriented end-user interfaces with pre-defined development concepts and building blocks, system interfaces to a concrete virtual world building tool, and a database to permanently maintain data used in *iVirtualWorld*. The second phase extended *iVirtualWorld* to the domain Biology and enhanced it by providing end-users certain flexibilities to adapt the system to their requirements using outside resources. The evaluation has been conducted based on the virtual presentations and these two major development phases. This chapter presents the details of the virtual presentations evaluation and user studies on the major development of *iVirtualWorld*.

5.1 Virtual Presentations Evaluation

Several case studies and a usability study have been conducted to evaluate the prototype for building virtual presentations (Liu et al., 2013) for the following questions:

(1) Effectiveness: Can end users create their virtual worlds using *iVirtualWorld*?

(2) Ease of use: Do end users find it easy to create their virtual worlds using *iVirtualWorld*?

(3) Usefulness: Do end users consider *iVirtualWorld* useful?

Different evaluation methods have been applied to answer these questions. This section introduces the processes of different evaluations that have been done on *iVirtualWorld*, with discussions of the results of each evaluation.

5.1.1 Case Studies

To answer the first question (i.e. effectiveness), *iVirtualWorld* was introduced to a virtual gallery walk class activity in two middle schools and was presented to a technology conference. In all case studies, *iVirtualWorld* was used successfully by students and educators and received overwhelmingly positive feedback.

The gallery walk is a class activity that helps students learn knowledge in a collaborative way in several middle schools in Ohio (Schendel, Liu, Chelberg, & Franklin, 2008; Young et al., 2010). For a specific topic, students are given an assignment to design posters presenting their researching results about this topic. Students display their posters as a gallery in the classroom and share their opinions with each other by walking along the gallery. Virtual world technologies have been introduced to traditional gallery walk, in which students design their posters using software like Microsoft PowerPoint and export the posters to digital images. These posters were imported into a virtual gallery by graduate students from Ohio University. Teachers and students can login and walk through the virtual gallery from anywhere and at anytime, overcoming the space and time limitation of traditional physical gallery walk and saving costs for printing paper posters. The virtual gallery walk received positive feedback from most of the students and teachers because they could learn when having fun in the virtual world. One issue was that too much work of graduate students had been involved since they needed to help teachers build a virtual gallery and help students import posters to the virtual gallery. If any posters were modified, teachers or students had to rely on graduate students to make changes to the virtual gallery (Young et al., 2010).

The case studies introduced *iVirtualWorld* to teachers and students at Athens Middle School and Federal Hocking Middle School to build a virtual gallery walk by themselves. Students could create their own galleries with digital contents after being given a tutorial of *iVirtualWorld*. Students published their virtual galleries as a web page and invited teachers and other students to visit the galleries from a web browser. Teachers and students logged in with avatars, walked around the galleries and chatted online with each other (Young et al., 2010). Figure 5.1 demonstrates a museum of Elvis Presley created by a student at Federal Hocking Middle School using *iVirtualWorld*.

Figure 5.1: A museum about Elvis Presley, created by a student at Federal Hocking Middle School

iVirtualWorld was also presented to K-12 educators during the eTech Ohio Conference held in Columbus Ohio in February 2010, demonstrating the gallery walk application as a sample scenario. Educators who attended the hands-on *iVirtualWorld* workshop were able to build a gallery walk after a tutorial.

The results of above-mentioned case studies provided positive answers to the first evaluation question raised at the beginning of this section. However, there lacked a process to let end users evaluate *iVirtualWorld* and express their opinions. Besides, the results of the case studies could not answer the last two questions raised at the beginning of this section. Further evaluation of *iVirtualWorld* was designed and conducted as usability study and is described in the next subsection.

5.1.2 Usability Study

A pilot study was first conducted during the 2011 Ohio University Student Research and Creative Activity Expo (Liu et al., 2013). The author presented *iVirtualWorld* to Expo visitors, who were mostly college students, secondary school students, and teachers. Eight visitors (4 females and 4 males) responded to a survey after the presentation. The results of the pilot study showed that 1) *iVirtualWorld* was easy to learn; 2) virtual worlds generated by *iVirtualWorld* were useful. Seven visitors agreed that *iVirtualWorld* was easy to use. Based on this pilot study, an *iVirtualWorld* usability study was conducted using improved procedure and survey questions (Liu et al., 2013). This subsection describes the details of the usability study.

The usability study was conducted at Baker University Center at Ohio University (Approved by IRB under approval no. 11X097). Four moderate laptops were used for accessing *iVirtualWorld* website through the wireless network provided in Baker University Center. Participants were recruited through handouts, email messages and the word-of-mouth. The study was anonymous so that there was no any connection between participants' identifications to their responses to the study. The procedure of the usability study consisted of the following steps (Liu et al., 2013):

1. The first step was a five-minute tutorial. Investigators introduced *iVirtualWorld* to participants and did a demo showing how to use *iVirtualWorld*.
2. In the second step, each participant was given a task to build a virtual classroom presenting Geology related materials. The participant was asked to build a Geology classroom using the small virtual world template. Participants followed a written task list describing the details of the tasks. Each participant was asked to build the classroom using four images, one presentation, one video and one 3D model pre-uploaded to *iVirtualWorld*. Participants could also choose to search for and use an arbitrary image that they upload by themselves.
3. Once participants finished building their virtual worlds, they could visit the virtual worlds to explore.
4. Lastly, they were asked to respond to a questionnaire containing 5-points Likert-Scale questions, yes/no questions, and open-ended questions.

Twenty-two participants (12 females and 10 males) attended the *iVirtualWorld* usability study, including 20 college students, 1 teacher, and 1 alumnus. The background information revealed that 16 participants (73%) had less than one year or no programming experience. Twenty participants (91%) had less than one year of virtual worlds building experience. Fifteen participants (68%) did not have any virtual worlds building experience. These participants well represented the average users, who typically had little or no programming skills and virtual worlds' experience and were the target population of *iVirtualWorld*.

All 22 participants successfully finished their task. Figure 5.2 shows one virtual classroom created by a participant, with 5 images, a PowerPoint file, a video, and a 3D model placed in the museum. There were three cases, in which images were not displayed after the first building process. Under the help of the investigators, these images were shown correctly inside the virtual worlds after a second building process. This problem was not because of user errors but rather caused by the unstable wireless network in the building where the usability study was conducted.

Figure 5.2: The Geology classroom created by a participant during *iVirtualWorld* usability study

Table 5.1 presents 22 responses to the 5-point Likert-Scale questions. Although in the table, these questions are categorized into three categories in terms of "ease of learning", "ease of use" and "usefulness" of *iVirtualWorld*, they were presented to participants ungrouped to avoid any possible unintended influences. Table 5.2 shows the statistics of the 22 responses. The central tendency of responses to each question is summarized using the median. The inter-quartile range (IQR) measures the statistical dispersion. The responses to “strongly disagree” and “disagree” are combined as one category “disagree”, and the responses to “agree” and “strongly agree” are combined as one category “agree”. Binomial test has been applied to responses to test whether the differences between responses to “disagree” and “aggress” are statistically significant.

Table 5.1: Responses to 5-point Likert-Scale questions (N =22)

Questions	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
Ease of Learning					
Q1. After the 5 minutes training, I was confident to create a virtual world using *iVirtualWorld*	0 (0.0%)	1 (4.5%)	2 (9.1%)	10 (45.5%)	9 (40.9%)
Q2. *iVirtualWorld* contains concepts that I do not understand	4 (18.2%)	11 (50%)	4 (18.2%)	2 (9.1%)	1 (4.5%)
Q3. Overall, *iVirtualWorld* is easy to learn	0 (0.0%)	0 (0.0%)	3 (13.6%)	12 (54.5%)	7 (31.8%)
Ease of use					
Q4. The 6-step wizard is designed in an intuitive order	1 (4.5%)	0 (0.0%)	1 (4.5%)	11 (50%)	9 (40.9%)
Q5. The prompt messages on web pages are useful and easy to understand	0 (0.0%)	0 (0.0%)	2 (9.1%)	14 (63.6%)	6 (27.3%)
Q6. The template floor plan is clear and easy to understand	0 (0.0%)	0 (0.0%)	0 (0.0%)	15 (68.2%)	7 (31.8%)
Q7. It is easy to find the assets required for the task	0 (0.0%)	1 (4.5%)	0 (0.0%)	10 (45.5%)	11 (50%)
Q8. I can create a virtual world without programming skills	1 (4.5%)	3 (13.6%)	2 (9.1%)	11 (50%)	5 (22.7%)
Q9. I can create a virtual world without 3D modeling skills	2 (9.1%)	2 (9.0%)	1 (4.5%)	13 (59.1%)	4 (18.2%)
Q10. Overall, it is easy to create a virtual world using *iVirtualWorld*	0 (0.0%)	1 (4.5%)	3 (13.6%)	10 (45.5%)	8 (36.4%)
Usefulness					
Q11. *iVirtualWorld* can be useful for my study or work	1 (4.5%)	2 (9.1%)	10 (45.5%)	6 (27.3%)	3 (13.6%)
Q12. The virtual world generated using *iVirtualWorld* is useful	1 (4.5%)	0 (0.0%)	3 (13.6%)	14 (63.6%)	4 (18.2%)

Nineteen participants (86.4%) felt confident to use *iVirtualWorld* after the five-minute training, which was a short amount of time concerning learning a new software tool. The responses to this question showed that *iVirtualWorld* was easy to learn in a short amount of time. The domain-oriented representations provided by *iVirtualWorld* encapsulate programming and 3D modeling details, which speeded up the learning process. Therefore over 60% participants understood all concepts in *iVirtualWorld.* Overall, 86.4% participants responded that *iVirtualWorld* was easy to learn. Statistical results show that the p-value for each question concerning ease-of-learn is less than 0.05, which implies positive responses to ease-of-learn of *iVirtualWorld* from participants.

The ease-of-use of *iVirtualWorld* was evaluated concerning the wizard, the floor plan, the notification messages on web pages, the asset search interface, and whether or not programming and 3D modeling skills were needed. Twenty participants (90.9%) agreed that the wizard was designed in an intuitive order, which implies ease-of-use. All of the participants considered that the template floor plan, which is a key element of *iVirtualWorld*, was easy to understand. Twenty participants (90.9%) found the notification messages easy to understand. The assets searching for the virtual world building is another important feature and 21 participants (95.5%) thought that it was easy to find an asset. More than 70% of the participants reflected that they did not need programming or 3D modeling skills to build virtual worlds using *iVirtualWorld*, which simplified their work. Overall, 18 participants (81.8%) considered *iVirtualWorld* easy to use. Statistical results show that the p-value for each question concerning ease-of-use is less than 0.05, which implies positive responses to ease-of-use of *iVirtualWorld* from participants.

Table 5.2: Statistics of 5-point Likert-Scale questions (N =22)

Questions	**Median**	**IQR**	**Disagree**	**Agree**	**p-value**
Ease of Learning					
Q1	4	1	1	19	<0.0001
Q2	2	1	15	3	0.003
Q3	4	1	0	19	<0.0001
Ease of use					
Q4	4	1	1	20	<0.0001
Q5	4	1	0	20	<0.0001
Q6	4	1	0	22	<0.0001
Q7	5	1	1	21	<0.0001
Q8	4	2	4	16	0.005
Q9	4	0	4	17	0.003
Q10	4	1	1	18	<0.0001
Usefulness					
Q11	3	1	3	9	0.05
Q12	4	0	1	18	<0.0001

Nine participants (40.9%) considered that *iVirtualWorld* could be useful for their study or work. The differences between “disagree” and “agree” is not significant (p=0.05). This was likely because virtual worlds were new to them and it was reasonable that they could not connect virtual worlds with their study or work right away. However, most of the participants believed that the generated virtual worlds could be useful. Two yes/no questions supplemented the evaluation of the usefulness. Eighteen participants (81.8%) chose "yes" for the question "*will you recommend iVirtualWorld to a teacher or a museum curator?*”, which meant that they thought *iVirtualWorld* was useful to teachers or museum curators. The reasons that participants chose “yes” included that “*it looks better than 2D*”,”*it would help students who miss class*”, “*it looks amazing*”, and it was “*easy to use and setup*”. One participant selected “no” for the reason that *iVirtualWorld* was “*too simplistic*”. When asked "*will you use iVirtualWorld if you were asked to present your content in a virtual 3D setting?*” 14 participants (63.6%) responded that they would use *iVirtualWorld* because "*it is so easy to use*", "*easy to learn*", "*it is more interactive than PPT*", and "*setup time is minimal*". Those who answered "no" to this question thought that *iVirtualWorld* was irrelevant to their study or *iVirtualWorld* was too technological for their presentations.

5.1.3 Discussion

This usability study received positive responses from participants. Most of the participants appreciated the ease-of-learn, the ease-of-use, and the usefulness of *iVirtualWorld*. These results justify the further development of *iVirtualWorld*. The responses reflected participants' true feelings about *iVirtualWorld* since they attended the study anonymously.

During the initial stage of this project, it was helpful to obtain feedback from potential users as soon as possible. This study was designed to focus on learnability, ease-of-use and usefulness of *iVirtualWorld* to general computer users, which is a broader population than educators. Since educators are considered as a subset of general computer users, results from this study can be applied for educators in terms of learnability, ease of use and usefulness of *iVirtualWorld*. With further development of *iVirtualWorld*, more studies targeting educators have been designed and conducted, which will be presented in following sections.

Participants responded that the templates provided by *iVirtualWorld* were insufficient and should be extended to fields such as Linguistics or Chemical Engineering, which conformed to the ultimate goal of this study.

In summary, the case studies showed that non-technical end users could use *iVirtualWorld* to build their own virtual worlds. Most of the participants who attended the separate usability study evaluated *iVirtualWorld* easy to learn, easy to use, and useful in education, museums, or the participants' own domains. The three evaluation questions raised at the beginning of this section obtained the positive confirmation through the case studies and the usability study on the implementation of the solution in the virtual presentation domain.

5.2 Evaluation of Domain-Oriented Interfaces and the First Two Levels of Adaptation[1]

After *iVirtualWorld* was extended from the virtual presentation domain to the chemistry experimental education domain by implementing the domain-oriented design and the first two levels of adaptation discussed in chapter 4, the first usability study was designed and conducted to evaluate the work at that time (Approved by IRB under approval no. 11X097). Usability evaluation of a user-computer interactive system involves three major measures: effectiveness, efficiency, and satisfaction (Hornbæk, 2006). According to a previously proposed evaluation plan (Zhong & Liu, 2012), *iVirtualWorld* is evaluated against the following questions:

- Effectiveness: Can end-users create 3D virtual chemistry experiments without programming and 3D modeling skills? Do end-users consider the 3D virtual experiments created using this methodology are useful for education?

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[1] The work described in this section has been submitted as the following paper:
Zhong, Y., & Liu, C. (2013a). A domain-oriented end-user design environment for generating interactive 3D Virtual Chemistry Experiments. *Multimedia Tools and Applications*. (Accepted with required minor revision)

- Efficiency: Can end-users create 3D virtual chemistry experiments in a reasonably short amount of time?
- Satisfaction: Do end-users think that *iVirtualWorld* is easy to learn and easy to use?

To answer these research questions, the following hypotheses are identified.

- The method enables average non-technical end-users to create effective virtual chemistry experiments in a reasonably short amount of time without programming and 3D modeling skills.
- The average non-technical end-users consider the tool implementing the method easy to learn and easy to use.
- The average non-technical end-users consider the method is useful.

This study was conducted from March to April in 2012. This section describes this study with details including the recruitment of participants and the demographical analysis, the procedure of the task session and the semi-structured interview. The results of the study are also presented with analysis and discussion.

5.2.1 Participants

Because *iVirtualWorld* is designed for the chemistry education domain, the target population is chemistry educators. The most important criterion for selecting participants was that they must be inside the target population; that is, chemistry educators. Recruitment message was sent to Teaching Assistants who were working as laboratory instructors in the Department of Chemistry at Ohio University. In order to increase the diversity of the participants, recruitment emails were also sent to science teachers who were teaching chemistry in several high schools in Ohio. There were a total of fourteen participants who attended the evaluation, with ten from Ohio University and four from Pickerington High School. All participants filled out a background survey to provide their basic information including gender, working experience in their domain, computer programming experience and virtual worlds' experience.

There was an even gender distribution among the 14 participants since half of them were male and half were female. Figure 5.3 (a) also shows an evenly distributed domain working experience. Most of the participants had less than one year of computer programming experience as shown in Figure 5.3 (b), which can be considered they had almost no programming experience. This was also confirmed during the semi-structured interview later. Eleven participants had never heard about or used any virtual worlds before attending the user study. Three participants used Second Life before but only explored the lands. None of the participants had experience creating 3D objects by themselves. The demography of the participants shows that they represented the target population, in which people have no 3D modeling and programming experience.

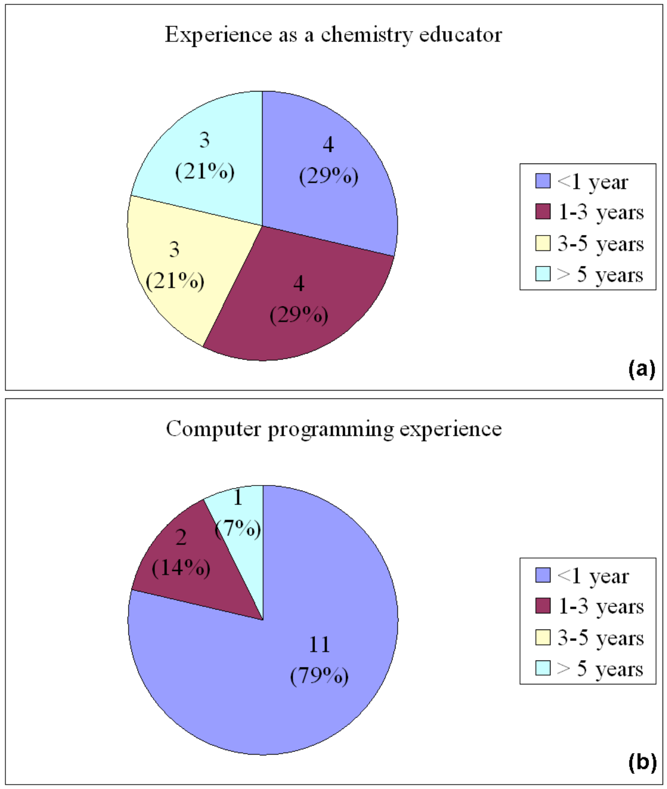

Figure 5.3: The distribution of participants' prior experience (a) in the domain and (b) of the computer programming

Before the user study, it was expected that most of the participants had experienced at least one 3D virtual world because of the popularity of 3D virtual worlds. However, the background survey revealed that only three participants had used 3D virtual worlds before. Most of the participants had no 3D virtual worlds experience at all before this study. When they were asked how they thought the possibility to create a 3D virtual experiment by themselves in the background survey, only one participant responded that "*it is possible because creating 3D virtual experiment is easy for me*", twelve participants considered that "*it is difficult for me but I can learn it if I have to.*" and one participant thought that "*it is very difficult for me and I do not have time and energy to learn it*". The answers to this question revealed participants' attitude towards building 3D virtual experiments by themselves. Most of them thought it was difficult for them. However, they expressed their willingness to learn it because it is useful.

5.2.2 Procedure

The user study was conducted in two parts. The first part was a task session required participants to finish a task using *iVirtualWorld* after a tutorial. Quantitative data (number-of-completion, time-of-completion, and responses to the Likert-Scale questions in the after task survey) and qualitative data (responses to open-ended questions in the after task survey) were collected from this part to answer the evaluation questions. The second part was a voluntary semi-structured interview in order to further probe participants' opinions that might have been neglected in the task session.

1. The task session

The task session was conducted in four steps:

1) Participant filled out an anonymous background survey about their personal information such as gender and previous experience on chemistry education, computer programming, and virtual worlds. The complete background survey can be found in Appendix A.1.1 Background Survey.

2) A researcher give a 15-minute tutorial, introducing the background of virtual worlds' application on chemistry education and *iVirtualWorld*, demonstrating the usage of *iVirtualWorld* interfaces, and showing the basic operations of *iVirtualWorld*. The tutorial focused on the operations of individual instrument or chemical and tried to avoid any hints to the task. The purpose of doing this was to see if participants could combine

those individual domain-oriented concepts together to make a workable chemistry experiment using *iVirtualWorld*. The tutorial also included the navigation and manipulation inside the 3D space.

3) After the tutorial, a same task was assigned to each participant with one page printed task description (Appendix B.1 Phase 1 Usability Study Task Description (As Distributed to Participants)). The task assumed that each participant was a chemistry teacher who wanted to take advantage of virtual worlds and to prepare a 3D virtual Total Dissolved Solids (TDS) experiment for his/her students. In case participants did not know the procedure of the TDS experiment, a detailed description of the procedure of this experiment was listed in the task description in natural language. To finish the task, participants needed to identify instruments and chemicals provided in *iVirtualWorld* that could be used in preparing such a 3D virtual experiment. Once participants found all the objects needed, they assembled those objects together and built the virtual experiment using *iVirtualWorld* design interfaces. When the virtual TDS experiment was built successfully, participants were encouraged to conduct the experiment by themselves in order to assess if it was correctly built up and could be used successfully.4) At the end of the task session, participants reflected their opinions and comments by filling out an anonymous online survey concerning the user study and *iVirtualWorld*. The survey included 5-point Likert-Scale questions, yes/no questions and open-ended questions. The complete questionnaires can be found in Appendix A.1.2 Questionnaires.

2. The voluntary semi-structured interview

After participants finished the task, they were invited to attend a voluntary 30-minute semi-structured interview to further express their personal feelings of *iVirtualWorld*. Researchers in Human-Computer Interaction field commonly apply semi-structured interviews to study participants' attitude and perception about a certain topic in depth (Dorn, 2010; Wiedenbeck, 2005). Researchers prepare several questions to discuss with participants but new questions or topics might be explored during the interview (Wiedenbeck, 2005). The questions prepared for the semi-structured interview were:

1) Do you think 3D virtual experiments are helpful for students to understand chemistry concepts? Specifically to what extent and to what point 3D virtual experiments are helpful?
2) Do you think 3D virtual experiments are helpful for students to understand the procedure better than traditional pre-lab? Why? If yes, specifically to what extent and to what point 3D virtual experiments are helpful?
3) Talk about your experience of using 3D virtual worlds in education?
4) What improvements does *iVirtualWorld* need?

A researcher interviewed with one participant at a time. Each interview was audio recorded for future transcription and analysis.

5.2.3 Results

This section presents the results of the task session and the semi-structured interview.

1. The task session

All 14 participants completed their tasks and the average time-of-completion was 25 minutes. Figure 5.4 shows a 3D virtual TDS experiment built by a participant. Compared to the time used by computer professionals to create such a virtual environment using traditional 3D virtual world building tool, the average time-of-completion 25 minutes can be considered very short.

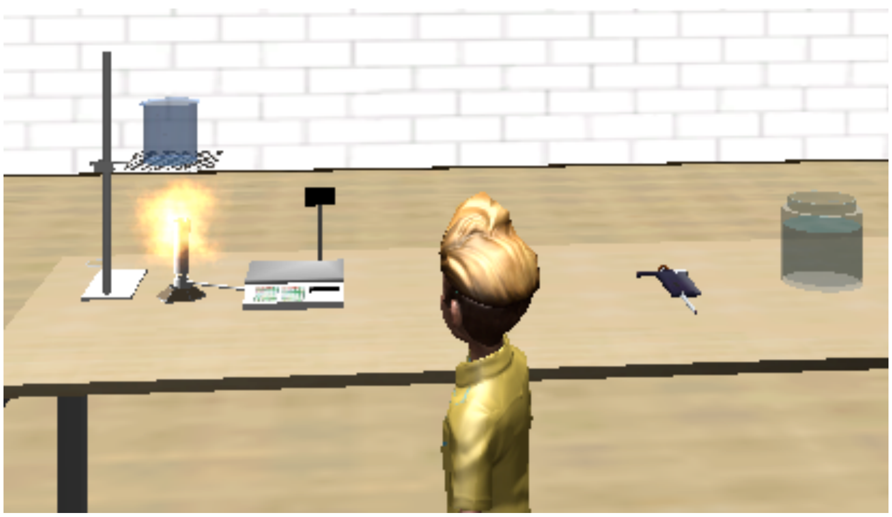

Figure 5.4: A 3D virtual TDS experiment created by a participant

Table 5.3 lists participants' responses to 5-point Likert-Scale questions concerning the learnability of *iVirtualWorld*. Eleven (78.6%) participants and 9 (64.3%) participants agreed that they did not need extra training on 3D modeling technologies and computer programming, separately, when using *iVirtualWorld*. Overall, thirteen (92.8%) participants considered *iVirtualWorld* easy to learn.

Table 5.3: Responses of the learnability of *iVirtualWorld* (N=14)

	Strongly disagree (1)	**Disagree (2)**	**Neutral (3)**	**Agree (4)**	**Strongly agree (5)**
QL1. I do not need extra trainings about 3D modeling technologies to create a 3D virtual experiment using *iVirtualWorld*	1 (7.1%)	0 (0.0%)	2 (14.3%)	9 (64.3%)	2 (14.3%)
QL2. I do not need extra trainings about computer programming skills to create a 3D virtual experiment using *iVirtualWorld*	1 (7.1%)	1 (7.1%)	3 (21.4%)	2 (14.3%)	7 (50.0%)
QL3. Overall, I think *iVirtualWorld* is easy to learn	0 (0.0%)	0 (0.0%)	1 (7.1%)	5 (35.7%)	8 (57.1%)

The statistics of the responses in Table 5.3 are summarized in Table 5.4. The central tendency of responses to each question is summarized using the median. The statistical dispersion is measured using IQR. The responses to "strongly disagree" and "disagree" are combined as one category "disagree", and the responses to "agree" and "strongly agree" are combined as one category "agree". Binomial test has been applied to responses to test whether the differences between responses to "disagree" and "aggress" are statistically significant. The results, i.e. $p<0.05$ for each question, show that the number of responses to "agree" is significantly greater than the number of responses to "disagree", which implies positive responses to the learnability of *iVirtualWorld* from participants.

Table 5.4: Statistics of the learnability of *iVirtualWorld* (N=14)

	Median	**IQR**	**Disagree**	**Agree**	**p-value**
QL1	4	0	1	11	0.003
QL2	5	2	2	9	0.03
QL3	5	1	0	13	0.0001

Table 5.5 summarizes participants' responses to 5-point Likert-Scale questions concerning the effectiveness of *iVirtualWorld*. Specifically, researchers want to know 1) if the domain-oriented interfaces are easy for end-users to understand and use; 2) can participants build 3D virtual experiments using their domain knowledge. All of the participants responded that the layout of the interfaces is easy to understand and they could easily finish their tasks with domain knowledge. Ten (71.4%) participants confirmed that the similarity of designing a virtual chemistry experiment using *iVirtualWorld* and designing a real world experiment. Therefore, the answers to the two aforementioned questions were positive. Overall, participants considered that it was easy to finish the task using *iVirtualWorld*.

The statistics of the responses in Table 5.5 are summarized in Table 5.6. The central tendency and the dispersion are measured by median and IQR. The responses to "strongly disagree" and "disagree" are combined as one category "disagree", and the responses to "agree" and "strongly agree" are combined as one category "agree". Binomial test has been applied to applicable responses to test whether the differences between responses to "disagree" and "aggress" are statistically significant. The results, i.e. $p<0.05$ for each question, show that the number of responses to "agree" is significantly greater than the number of responses to "disagree", which implies positive responses to the effectiveness of *iVirtualWorld* from participants.

Table 5.5: Responses of effectiveness of *iVirtualWorld* (N=14)

	Strongly disagree (1)	**Disagree (2)**	**Neutral (3)**	**Agree (4)**	**Strongly agree (5)**
QE1. The layout of "creating virtual experiment" web page is designed in a way that I can easily understand	0 (0.0%)	0 (0.0%)	0 (0.0%)	7 (50.0%)	7 (50.0%)
QE2. It is easy to design the virtual TDS experiment using *iVirtualWorld* by reading the experiment description provided	0 (0.0%)	0 (0.0%)	0 (0.0%)	6 (42.9%)	8 (57.1%)
QE3. Designing a virtual experiment using items in the inventory provided by *iVirtualWorld* is similar to designing a real experiment	0 (0.0%)	1 (7.1%)	3 (21.4%)	5 (35.7%)	5 (35.7%)
QE4. I feel comfortable to use *iVirtualWorld*	0 (0.0%)	0 (0.0%)	3 (21.4%)	6 (42.9%)	5 (35.7%)
QE5. I can easily finish my task with my knowledge of chemistry (e.g. TDS) by using *iVirtualWorld*	0 (0.0%)	0 (0.0%)	0 (0.0%)	6 (42.9%)	8 (57.1%)
QE6. The ability of changing instruments' settings can help me create different experiments as I wish	0 (0.0%)	1 (7.1%)	2 (14.3%)	5 (35.7%)	6 (42.9%)
QE7. Overall, I can easily build a virtual TDS experiment using *iVirtualWorld*	0 (0.0%)	0 (0.0%)	0 (0.0%)	6 (42.9%)	8 (57.1%)

Table 5.6: Statistics of effectiveness of *iVirtualWorld* (N=14)

	Median	**IQR**	**Disagree**	**Agree**	**p-value**
QE1	5	1	0	14	<0.0001
QE2	5	1	0	14	<0.0001
QE3	4	2	1	10	0.005
QE4	4	1	0	11	0.0004
QE5	5	1	0	14	<0.0001
QE6	4	1	1	11	0.003
QE7	5	1	0	14	<0.0001

Table 5.7 presents the participants' responses to 5-point Likert-Scale questions concerning the efficiency of *iVirtualWorld*. Participants appreciated that creating 3D virtual experiments using *iVirtualWorld* was more economical and safer than preparing

physical experiments. Thirteen (92.8%) participants thought that creating 3D virtual experiments cost less time than preparing physical experiment.

Table 5.7: Responses of efficiency of *iVirtualWorld* (N=14)

	Strongly disagree (1)	**Disagree (2)**	**Neutral (3)**	**Agree (4)**	**Strongly agree (5)**
QI1. The process of creating a 3D virtual experiment in *iVirtualWorld* is designed in an efficient way so that I can build 3D virtual experiments in short time	0 (0.0%)	0 (0.0%)	0 (0.0%)	7 (50.0%)	7 (50.0%)
QI2. Creating a 3D virtual experiment using *iVirtualWorld* cost less time than preparing a physical experiment	0 (0.0%)	0 (0.0%)	1 (7.1%)	7 (50.0%)	6 (42.9%)
QI3. Creating a 3D virtual experiment using *iVirtualWorld* is more economical than preparing a physical experiment	0 (0.0%)	0 (0.0%)	0 (0.0%)	5 (35.7%)	9 (64.3%)
QI4. Creating a 3D virtual experiment using *iVirtualWorld* is safer than preparing a physical experiment	0 (0.0%)	0 (0.0%)	0 (0.0%)	6 (42.9%)	8 (57.1%)
QI5. Creating a 3D virtual experiment using *iVirtualWorld* is convenient because I can do it anytime and anywhere with a computer and Internet	0 (0.0%)	0 (0.0%)	0 (0.0%)	7 (50.0%)	7 (50.0%)

The statistics of the responses in Table 5.7 are summarized in Table 5.8. The central tendency of responses to each question is summarized using the median. The IQR measures the statistical dispersion. The responses to “strongly disagree” and “disagree” are combined as one category “disagree”, and the responses to “agree” and “strongly agree” are combined as one category “agree”. Binomial test has been applied to responses to test whether the differences between responses to “disagree” and “aggress” are statistically significant. The results, i.e. $p<0.05$ for each question, show that the number of responses to "agree" is significantly greater than the number of responses to "disagree", which implies positive responses to the efficiency of *iVirtualWorld* from participants.

Table 5.8: Statistics of efficiency of *iVirtualWorld* (N=14)

	Median	**IQR**	**Disagree**	**Agree**	**p-value**
QI1	5	1	0	14	<0.0001
QI2	4	1	0	13	0.0001
QI3	5	1	0	14	<0.0001
QI4	5	1	0	14	<0.0001
QI5	5	1	0	14	<0.0001

Table 5.9 reflects the participants' responses to 5-point Likert-Scale questions concerning the satisfaction of *iVirtualWorld*. All of the participants found that *iVirtualWorld* was useful for Chemistry teachers. Twelve (85.7%) participants were satisfied with *iVirtualWorld* overall and thought that it was easy to use.

Table 5.9: Responses of satisfaction of *iVirtualWorld* (N=14)

	Strongly disagree (1)	**Disagree (2)**	**Neutral (3)**	**Agree (4)**	**Strongly agree (5)**
QS1. I would find *iVirtualWorld* useful for Chemistry teachers	0 (0.0%)	0 (0.0%)	0 (0.0%)	10 (71.4%)	4 (28.6%)
QS2. Overall, I am satisfied with *iVirtualWorld*	0 (0.0%)	0 (0.0%)	2 (14.3%)	7 (50.0%)	5 (35.7%)
QS3. Overall, I think *iVirtualWorld* is easy to use	0 (0.0%)	0 (0.0%)	2 (14.3%)	6 (42.9%)	6 (42.9%)
QS4. Three-dimensional virtual world technologies are useful in education	0 (0.0%)	0 (0.0%)	1 (7.1%)	7 (50.0%)	6 (42.9%)

The statistical results of the responses in Table 5.9 are summarized in Table 5.10. The central tendency of responses to each question is summarized using the median. The inter-quartile range (IQR) measures the statistical dispersion. The responses to "strongly disagree" and "disagree" are combined as one category "disagree", and the responses to "agree" and "strongly agree" are combined as one category "agree". Binomial test has been applied to responses to test whether the differences between responses to "disagree" and "aggress" are statistically significant. The results, i.e. $p<0.05$ for each question, show that the number of responses to "agree" is significantly greater than the number of responses to "disagree", which implies positive responses regarding satisfaction in using *iVirtualWorld* from participants.

Table 5.10: Statistics of user satisfaction of using *iVirtualWorld* (N=14)

	Median	**IQR**	**Disagree**	**Agree**	**p-value**
QS1	4	1	0	14	<0.0001
QS2	4	1	0	12	0.0002
QS3	4	1	0	12	0.0002
QS4	4	1	0	13	0.0001

In the survey of the task session, participants were also asked about their attitude to creating 3D virtual experiments by themselves using *iVirtualWorld*. All of the 14 participants responded that creating 3D virtual experiments was easy for them by using *iVirtualWorld*. Before the task session, only one participant was confident on creating 3D virtual experiments by him/her. Comparing the responses before and after the task session, *iVirtualWorld* significantly increased participants' confidence of creating 3D virtual experiments by themselves ($p<0.0001$). This confidence increase might encourage them to consider applying virtual worlds in their education in the future.

2. Semi-structured interview

In semi-structured interviews, the author had a one-on-one conversation with one participant at one time to further solicit their feedback of *iVirtualWorld*, as well as observe their attitude about the application of virtual worlds in education. The conversation focused on the usefulness of 3D virtual experiments in teaching chemistry concepts and experiment procedures, participants' experience of virtual worlds, and improvement of *iVirtualWorld*. Eleven participants attended the interview and their responses are summarized as following.

1) Usefulness of 3D virtual experiments in teaching chemistry concepts

All of the interviewees admitted the usefulness of 3D virtual experiments in teaching chemistry concepts. Specifically, interviewees identified several topics in chemistry that they think the 3D virtual experiments would be useful for, including biochemistry, analytical chemistry, and organic chemistry because these topics were considered "*completely empirical and completely hands-on*". On the other hand, physical chemistry and inorganic chemistry were “more theoretical” and would benefit less from 3D virtual experiments. A benefit for the organic chemistry was that applying 3D virtual experiments could demonstrate long-term reaction (e.g. 48 hours) to students in a short time, which saved pedagogical time. In more detail, interviewees identified that experiments involving concepts like pH, clarity, density, and hydrate might take advantage of 3D virtual experiments because of the visual effects.

2) Helpfulness of 3D virtual experiments in teaching experiment procedure

Interviewees from Ohio University appreciated the helpfulness of 3D virtual experiments in teaching experimental procedures, especially for the pre-lab. Pre-lab refers to the processes of students preparing for real experiments. At the Department of Chemistry at Ohio University, students are required to read the lab manuals and finish assignments before the lab sessions. Lab instructors also give a short lecture prior to the actual real world experiments. The purpose of the pre-lab is to familiarize students with content, procedures, and safety issues of the lab sessions. However, interviewees mentioned that students usually did not care much about the pre-lab because they either had no interest in reading the lab manuals or could not understand the content described in the text. Even the pictures and diagrams on the lab manuals rarely helped very much. These interviewees believed that introducing 3D virtual experiments to the pre-lab could 1) attract students' attention and increase students' interest; 2) familiarize students with new instruments in their 3D representations; and 3) explain the experiment procedures in a visual and dynamic manner, and in turn help students better understand the real world experiments. One interviewee who was an organic chemistry lab instructor even invited the researcher to attend their lab session because he saw a huge potential of *iVirtualWorld* on helping students of pre-lab.

Interviewees were clearly aware of that 3D virtual experiments could not completely replace traditional real world experiments after they used *iVirtualWorld*. The operation of some instruments needs practice in a real world lab. For instance, the manipulation of the autopipette is quite simple in the *iVirtualWorld*. However, in the real world, one needs to be cautious about how to hold it in hand, how to adjust the volume precisely, and how deep the tip can be inserted into the solution. Those skills have to be practiced in real world hands-on experiments and could not be obtained only by current 3D virtual environments. Nevertheless, interviewees realized that the combination of 3D virtual experiments with real world experiments would be more useful than the real world experiments alone.

Most of the interviewees brought out the safety issues during the interview. They noticed that the features of 3D virtual environments could be utilized to simulate or demonstrate operations that could cause problems in the real world, without wasting instruments and chemicals or threatening the health and safety of teachers and students.

3) Comparison of *iVirtualWorld* with real world experiments:

The TDS experiment designed for the user study was adapted from a real world experiment used at Ohio University Chemistry Department. Interviewees who were laboratory instructors were familiar with the real world counterpart of the virtual TDS experiment. So they made comments during the interview about the comparison of *iVirtualWorld* with real world experiments. The virtual experiments run faster than real world experiments. A reaction or operation in a real world experiment may need long time waiting. For example, an organic reaction could take 48 hours to finish. In virtual experiments, the time could be scaled down to minutes or seconds, which can be efficient for educational purposes, especially for demonstrations that need to be repeated a lot. Interviewees also realized that virtual experiments are more safe and economical than real world experiments because they would not worry about wasting expensive chemicals or breaking equipment. Interviewees confirmed the usefulness of virtual experiments as an auxiliary to real world experiments.

4) Improvement of *iVirtualWorld*

During the interview, interviewees were asked to suggest improvements for *iVirtualWorld* since they are potential end-users. Insufficient domain-oriented concepts, camera view in the 3D virtual space, precise movement of 3D objects were major concerns from interviewees.

a. Insufficient domain-oriented concepts

Although interviewees were from the domain of chemistry education, each one had his or her specialty. Therefore, in addition to the general introductory chemistry experiments, they were looking for concepts from their specific areas. For example, an interviewee from organic chemistry expressed his high interest in *iVirtualWorld* and suggested more instruments and chemicals used in organic chemistry experiments. Incorporating more domain-oriented concepts and enabling end-users to upload 3D objects by themselves would be the work in phase 2.

b. Camera view

The virtual experiments built in Unity3D used the third-person view with avatars. The interviewees agreed that the avatar increased the entertainment of playing with the virtual experiments. However, most of interviewee felt uncomfortable when there was a limited zoom-in range. They expected closer inspection of instruments they manipulated just like they could do in a real experiment.

c. Manipulation of 3D objects

iVirtualWorld provides 3D objects manipulation in a virtual 3D space using a mouse. Moving the mouse left and right moves a 3D object left and right (along x-axis) in the virtual 3D space. The 3D object is moved forward and backward when the players move the mouse forward and backward (along z-axis). By scrolling the mouse wheel up and down, the player moves the object up and down (along y-axis) in the 3D virtual space. Interviewees expressed that this method was naturally simulated the manipulation of a 3D object in a real 3D space. However, they also indicated that it was difficult for them to do very precise manipulation when they needed to interact with more than one 3D object. For instance, the virtual TDS experiment required users to insert an autopipette into a beaker. This operation could be hard for interviewees because the problem of displaying 3D space on a 2D computer screen. Interviewees found that from the screen the autopipette had been inserted in to the beaker but in fact these two objects had different depths (z-coordinates). Even with a second top-view of the virtual experiment, interviewees still thought this could be a problem at the beginning since they were not proficient to use two different views at the same time. Nevertheless, just like one interviewee said, "*once you get used to the interface, it became more straighter*." Several interviewees felt the same way.

d. Mobility

One interviewee noticed the popularity of mobile devices among students and strongly suggested a mobile version of the 3D virtual chemistry experiments. The interviewee pointed out that students could play with 3D virtual experiments on their Smartphones or tablets anytime and anywhere, even when they are waiting on line at a popular restaurant or lying on the beds before sleeping. Furthermore, the touch screen enables closer interaction between fingers and 3D virtual objects, which brings students more realistic feelings than using a mouse. Mobility of the 3D virtual chemistry experiments could be an important trend.

5.2.4 Discussion

The results from the task session that participants could successfully build a 3D virtual experiment in a short amount of time using *iVirtualWorld* proved the effectiveness and efficiency of this solution. The responses to the post-task survey confirmed that *iVirtualWorld* was easy to learn and easy to use because of its domain-oriented interfaces. The 3D virtual chemistry experiments built by *iVirtualWorld* were assessed by participants as useful for teaching certain chemistry concepts and for preparing students with real experiments.

Participants gained confidence of creating 3D virtual world technologies after they were introduced to *iVirtualWorld*. Most of the participants had no confidence on building 3D virtual chemistry experiments by themselves before the user study. After using *iVirtualWorld*, they all believed that they could create 3D virtual chemistry experiments by themselves. This confidence increase could encourage them to apply virtual worlds in their class in the future, and in turn widen the application of virtual world technologies in education.

Because most of the participants (71%) were from the same organization, there might exist a sample diversity limitation. Besides, the usefulness of the 3D virtual chemistry experiments generated by *iVirtualWorld* was evaluated by participants as chemistry educators. Lack of the classroom assessment of the educational effects of the 3D virtual experiments on students could bring limitation to the evaluation. However, the main purpose of the evaluation so far was to assess the effectiveness of the domain-oriented interfaces and the target audiences are chemistry educators. Therefore, participants who attended this study were valid of their representation.

Only one scenario (3D virtual TDS experiment) was applied in the user study to evaluate *iVirtualWorld*, emphasizing the ease-to-learn and the ease-to-use of the domain-oriented end-user design interfaces. The TDS scenario comprised several basic operations in chemistry such as weighing, autopipette operation, Bunsen burner controlling and heating solution. Each of these basic operations could be used as a separate 3D virtual experiment. The ability of expanding to more experiments was not explicitly evaluated at this moment, but *iVirtualWorld* has potentials to create more scenarios than the TDS experiment.

5.3 Evaluation of the Third Level of Adaptation[2]

After the first phase development and evaluation of the solution, most of the efforts were dedicated to developing the third level of adaptation so that end-users could

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[2] The work described in this section has been submitted as the following paper:
Zhong, Y., & Liu, C. (2013b). Multi-Level Adaptation in End-User Development of 3D Virtual Chemistry Experiments. *International Journal of Virtual and Personal Learning Environments.* (Under Review)

extend current system with outside resources as designed in chapter 4. Besides, the application domain of *iVirtualWorld* was extended to Biology experiments too. The second usability study was designed to assess *iVirtualWorld* with respect to these new features (Approved by IRB under approval no. 12X220). Specifically, the study was planned to seek answers to these research questions:

- Can average non-technical users of *iVirtualWorld* create effective virtual experiments with the new feature that enabling the extension of current system by importing new 3D objects?
- Does *iVirtualWorld* increase average non-technical end-users' awareness and confidence on applying 3D virtual world technologies in education?

The following hypotheses are identified for this usability study:

- The solution enables average non-technical end-users to create effective virtual experiments with the new extension feature in a reasonably short amount of time, without programming and 3D modeling skills.
- The solution increases average non-technical end-users' awareness and confidence on applying 3D virtual world technologies in education.

The second usability study was conducted on November 3rd, 2012. This section describes this study with details including the recruitment of participants and the procedure of the task session. The results of the evaluation are also presented with analysis and discussion.

5.3.1 Participants

Participants were recruited from a Professional Development meeting hold by a NSF GK-12 project named BooKS (http://books.ohio.edu). The BooKS project intends to enrich science and engineering education of graduate students at Ohio University and to improve students' communication abilities through a series of activities related to their majors. Every year, graduate students are paired with high school science teachers to conduct water quality on a boat along Ohio River, using water samples collected from several monitoring locations from Marietta to Gallipolis. These graduate students then work with science teachers to bring these activities to their classroom to high school students. The BooKS project also provides professional development meetings for high school science teachers to improve their teaching technologies.

The author was invited to a session during the BooKS project professional development to present *iVirtualWorld* and to conduct the user study. Graduate students and high school teachers were recruited to attend this user study at the beginning of the session. Graduate students and teachers were informed with the details of the user study by a consent form, which told them that they were voluntary to attend the user study and could quit at anytime without any penalties. After participants had signed the consent forms, they were given a background survey to fill out. The background survey collected demographic data of participants. Specifically, this study inquired about participants' teaching experience, computer programming experience, 3D virtual world experience, and their attitudes to applying virtual world technologies in education. Eighteen participants filled out the background survey.

Most of the participants (59.3%) taught Chemistry or Biology. There were also teachers teaching Physical Science, Environmental Science, Anatomy, Physiology, and Earth Science. Some teachers were responsible for more than one subject. A teacher could teach both Chemistry and Physical Science. However, this fact would not influence the validity of this user study.

Most of the participants were experienced educators with more than five years teaching practice. 44.4% of them had computer programming experience less than one year. There were 27.8% participants responded that their programming experience was zero year. These two groups made about three quarters of participants were computer end-users with very little computer programming skills. Over half of the participants did not have much 3D virtual world experience, with 38.9% participants having no experience and 16.7% participants having less than 1 year experience. Only 5.5% participants had experience on 3D virtual world greater than 5 years.

In summary, the background survey reveals the features of the participants: they were experienced science (Chemistry and Biology) teachers with little programming and 3D virtual world experience. These features accorded with that of the target audience of this solution, which are non-technical average computer end-users, in the domain of Chemistry or Biology education.

5.3.2 Pre-Task Questionnaires

The background survey also asked several questions concerning participants' awareness and confidence of applying 3D virtual world technologies in education as pre-task questionnaires.

Participants were asked to vote for different factors that could prevent virtual worlds from being applied in education successfully. They could choose as many factors as they want, as well as provide their own answers. Figure 5.5 summarizes the voting results. The first three factors in Figure 5.5 were provided by the author, and the last two items were added by participants. The participants identified "Educators may face technical barriers when learning and using virtual worlds" as the number one factor preventing the successful application of virtual worlds in education. This finding conforms to the results obtained by Levine (2010) and strengthens the motivation and significance of the work presented in this dissertation. Other factors included insufficient educational materials, inappropriate content, limited computer availability, and skills that must be trained in the real world.

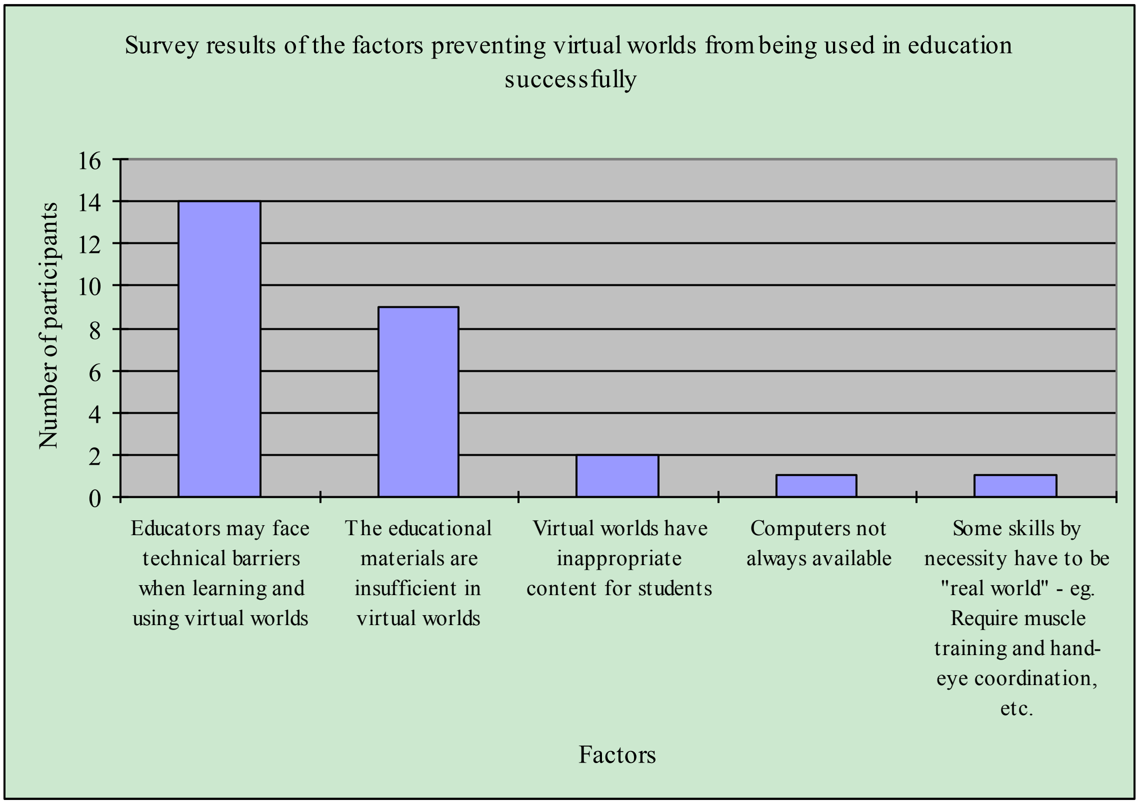

Figure 5.5: Survey results of the factors preventing virtual worlds from being used in education successfully

The pre-task questionnaires also asked participants' confidence of creating 3D virtual experiments by themselves. Only four participants explicitly answered that "*It is possible. Creating 3D virtual experiment is easy for me.*" Ten participants responded that "*It is impossible. Creating a 3D virtual experiment is very difficult for me.*" Other four participants had attitudes somewhere between these two choices. The same question was asked after participants finish their tasks to capture any possible changes of their attitudes on creating 3D virtual experiments.

5.3.3 Procedure

The user study session took about one hour and fifteen minutes. The whole process included a tutorial, a task, and a survey. The author, as the primary investigator, and three co-investigators worked together to assist participants and to answer their questions. The detailed procedure is described below.

At the beginning, the author briefly introduced the user study to all of the participants. Consent forms and background surveys were passed out to each participant. Participants then signed the consent forms and filled out the background survey. This step took about 5 minutes.

Next, the author gave a presentation about *iVirtualWorld*, including the background and the website tutorial, in 15 minutes. Participants were shown how to use the *iVirtualWorld* web interface to generate virtual experiments.

Then, the participants were given 45 minutes to complete a task. One teacher was paired with one graduate student so that two participants worked together as a group, which was a conventional organization for activities in the BooKS project. There were a total of 9 groups, each of which was provided a handout describing the task. The participants were asked to build a Dissolved Oxygen (DO) experiment (LaMOTTE, 2007) using *iVirtualWorld*. One instrument was missing in *iVirtualWorld* and needed to be imported by the participants from Google Warehouse. After building the virtual DO experiment, participants also required to get the experiment to test the result. The detailed description of this task and the DO experiment can be found in Appendix B.2. The participants who successfully built and conducted the virtual DO experiment were considered completing their task. An instruction document was also provided to each group to assist them to finish the task. The author and three co-investigators walked around the room to provide help to those participants.

At the end, the participants filled out post-task questionnaires in 10 minutes. The questionnaires contained 5-point Likert-Scale questions, yes-no questions, multiple-choice questions and open-ended questions. The complete questionnaires can be found in Appendix A.2.

5.3.4 Results

Among 9 groups, 7 groups (77% participants) finished their tasks in 45 minutes, including building and running the virtual DO experiment. The fastest group spent 16 minutes completing the task. The average completion time of these 7 groups was 32 minutes. The other 2 groups finished the building of the virtual DO experiment but could not complete the virtual experiment performance in time. Figure 5.6 shows a virtual DO experiment generated by a group using *iVirtualWorld*. Totally 13 responses to the questionnaires were handed back to researchers at the end of the user study. Five pairs of participants thought they only needed to respond to the exit questionnaires as a group, not individually, due to a miscommunication. While this reduced the number of data points for the study, the result still reflected the opinions of all participants. In this section, the results and analysis of the responses are presented.

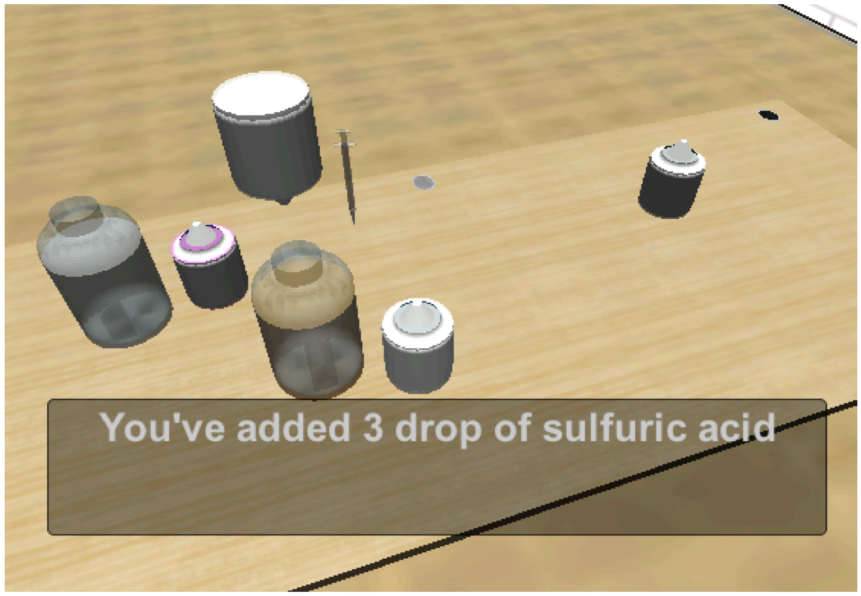

Figure 5.6: A virtual dissolved oxygen experiment created by a group

Table 5.11 lists the responses to the 5-point Likert-Scale questions based on 13 responses. Three questions were not answered in all of these 13 responses. In Table 5.11, questions that were not answered by all of the participants are marked with a star symbol (*) and the actual participant number is given in parentheses after this question.

Table 5.11: Responses to 5-point Likert-Scale questions (N=13)

	Strongly disagree (1)	**Disagree (2)**	**Neutral (3)**	**Agree (4)**	**Strongly agree (5)**
Q1. I do not need extra trainings about 3D modeling technologies to create a 3D virtual experiment using *iVirtualWorld*	3 (23.1%)	5 (38.5%)	1 (7.7%)	2 (15.4%)	2 (15.4%)
Q2. I do not need extra trainings about computer programming skills to create a 3D virtual experiment using *iVirtualWorld*	4 (30.8%)	2 (15.4%)	2 (15.4%)	2 (15.4%)	3 (23.1%)
Q3. The layout of "creating virtual experiment" web page is designed in a way that I can easily understand	0 (0.0%)	2 (15.4%)	3 (23.1%)	7 (53.8%)	1 (7.7%)
*Q4. Overall, I think *iVirtualWorld* is easy to learn (n=11)	0 (0.0%)	0 (0.0%)	4 (36.4%)	6 (54.5%)	1 (9.1%)
Q5. Setting up a virtual experiment using items in the inventory provided by *iVirtualWorld* is similar to what a teacher does in real life	0 (0.0%)	2 (15.4%)	5 (38.5%)	5 (38.5%)	1 (7.7%)
Q6. I feel comfortable using *iVirtualWorld*	1 (7.7%)	4 (30.8%)	4 (30.8%)	3 (23.1%)	1 (7.7%)
Q7. I can easily finish my tasks with my current knowledge background by using *iVirtualWorld*	0 (0.0%)	6 (46.2%)	3 (23.1%)	2 (15.4%)	2 (15.4%)
Q8. The ability of adding new instruments to *iVirtualWorld* is useful for setting up more experiments	0 (0.0%)	0 (0.0%)	1 (7.7%)	7 (53.8%)	5 (38.5%)
Q9. The process of creating a 3D virtual experiment in *iVirtualWorld* is designed in an efficient way so that I can build 3D virtual experiments in short time	0 (0.0%)	2 (15.4%)	7 (53.8%)	3 (23.1%)	1 (7.7%)
Q10. Setting up 3D virtual experiments using *iVirtualWorld* costs less time than preparing similar physical experiments	0 (0.0%)	3 (23.1%)	4 (30.8%)	4 (30.8%)	2 (15.4%)
Q11. Setting up 3D virtual experiments using *iVirtualWorld* is more economical than preparing similar physical experiments	0 (0.0%)	0 (0.0%)	3 (23.1%)	7 (53.8%)	3 (23.1%)
Q12. Setting up 3D virtual experiments using *iVirtualWorld* is safer than preparing similar physical experiments	0 (0.0%)	0 (0.0%)	3 (23.1%)	7 (53.8%)	3 (23.1%)
Q13. Setting up 3D virtual experiments using *iVirtualWorld* is convenient because I can do it anytime and anywhere with a computer with Internet access	1 (7.7%)	0 (0.0%)	3 (23.1%)	6 (46.2%)	3 (23.1%)
*Q14. I find *iVirtualWorld* useful for Chemistry or Biology teachers (n=12)	0 (0.0%)	2 (16.7%)	5 (41.7%)	4 (33.3%)	1 (8.3%)
Q15. Overall, I am satisfied with *iVirtualWorld*	0 (0.0%)	3 (23.1%)	9 (69.2%)	0 (0.0%)	1 (7.7%)
*Q16. Overall, I think *iVirtualWorld* is easy to use (n=12)	0 (0.0%)	4 (33.3%)	5 (41.7%)	2 (16.7%)	1 (8.3%)

Table 5.12 summarizes the statistics of the responses in Table 5.11. The central tendency of responses to each question is summarized using the median. The IQR measures the statistical dispersion. The responses to “strongly disagree” and “disagree” are combined as one category “disagree”, and the responses to “agree” and “strongly agree” are combined as one category “agree”. Binomial test has been applied to applicable responses to test whether the differences between responses to “disagree” and “aggress” are statistically significant.

Table 5.12: Statistics of 5-point Likert-Scale questions (N=13)

	Median	**IQR**	**Disagree**	**Agree**	**p-value**
Q1	2	2	8	4	0.12
Q2	3	4	6	5	0.23
Q3	4	1	2	9	0.02
Q4	4	1	0	7	0.008
Q5	3	1	2	6	0.1
Q6	3	2	5	4	0.25
Q7	3	2	6	4	0.2
Q8	4	1	0	12	0.0002
Q9	3	1	2	4	0.23
Q10	3	1	3	6	0.16
Q11	4	1	0	10	0.001
Q12	4	1	0	10	0.001
Q13	4	2	1	9	0.01
Q14	3	1	2	5	0.16

Four participants out of 13 participants agreed that they did not need extra training of 3D modeling technologies (Q1), and 5 participants out of 13 participants admitted that no extra training of computer programming was needed (Q2). Although most of the responses stated that they needed extra trainings on 3D modeling and programming, the differences between “disagree” and “agree” were not significant ($p>0.05$). Overall no participants considered that *iVirtualWorld* was hard to learn (Q4:

p<0.05). Especially they thought the layout of creating virtual experiments was easy to understand (Q3: p<0.05), which could be interpreted as that the user interface was easy to understand.

Twelve positive responses confirmed that "*The ability of adding new instruments to iVirtualWorld is useful for setting up more experiments*" (Q8: p<0.05). Although this user study directed participants to import one instrument 3D model from Google Warehouse to *iVirtualWorld* and the participants were not given a task to build an arbitrary virtual experiment using the extension feature, they could see its potential of extending current systems to set up more experiments than the one they were required to build.

The responses to the question "*Setting up a virtual experiment using items in the inventory provided by iVirtualWorld is similar to what a teacher does in real life*" were neutral (Q5: p>0.05) possibly because different schools or teachers had different real-life laboratory settings. Some of the real-life settings might be similar to what *iVirtualWorld* provides while some of that could be quite different. Further development could be suggested to explore different laboratory settings for end-users to choose.

The responses to questions such as "*I feel comfortable using iVirtualWorld*", "*I can easily finish my tasks with my current knowledge background by using iVirtualWorld*", "*Overall, I am satisfied with iVirtualWorld*", and "*Overall, I think iVirtualWorld is easy to use*" tended to be negative or neutral. However, the differences between the numbers of responses to the "disagree" and the numbers of responses to the "agree" are not significant (p>0.05) for these questions. The author noticed that participants could easily perform the tasks using the domain-oriented end-user design interfaces on the *iVirtualWorld* website. However, they encountered troubles when they tested the built virtual experiment in the 3D environment. In their responses to the open-ended questions, participants reflected that

"*it's easy to set up, but difficult to use*"

"*having more time to get familiar w/ the program would have helped me (due to a lack of experience w/ virtual worlds)*"

"*if the game becomes smoother and easier to use it could be a very useful tool*"

Since more than half of the participants did not have much 3D virtual world experience, navigating inside a 3D space and operating 3D objects could be difficult for them. However, as one participant wrote on the survey sheet, "*once I use the virtual chemistry lab more I will become comfortable with it*".

Most of the participants considered setting up 3D virtual experiments using *iVirtualWorld* as a more economical (Q11) and safe (Q12) way than preparing real-life experiments ($p<0.05$).

Participants were asked to vote for different problems that could be tackled by *iVirtualWorld*. The problems were the factors that could prevent virtual worlds from being used in education successfully appeared in the background survey. Participants could choose as many problems as they wanted, as well as provide their own answers. Figure 5.7 summarizes the results. Ten out of 13 (77%) participants believed that *iVirtualWorld* could address the problem that "*Educators may face technical barriers* *when learning and using virtual worlds*." The responses confirmed the usefulness of *iVirtualWorld* with participants' confidence.

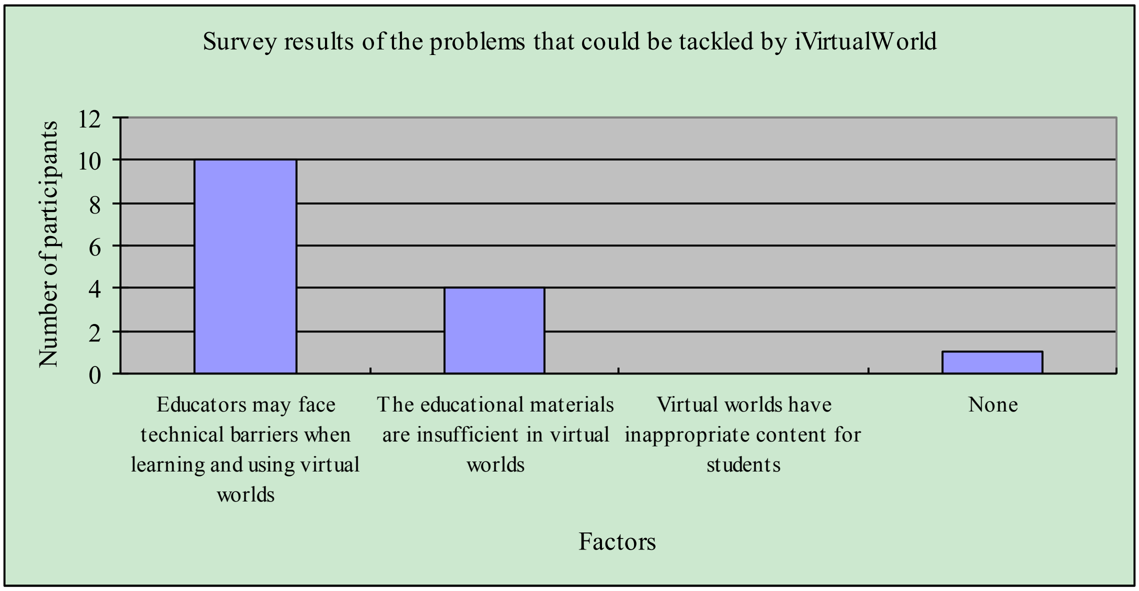

Figure 5.7: Survey results of the problems that could be tackled by *iVirtualWorld*

Participants were asked about their confidence on building 3D virtual experiments by themselves again in the post-task questionnaires. Seven participants chose that "*It is possible. Creating 3D virtual experiments is easy for me using iVirtualWorld.*" Six participants still considered that "*It is impossible. Creating a 3D virtual experiment is still difficult for me even using iVirtualWorld.*" An increase could be observed of the number of responses (from 4 to 7) considering that creating 3D virtual experiments was easy using *iVirtualWorld*.

5.3.5 Discussion

In this usability study, participants were given a task to build a virtual experiment employing *iVirtualWorld* with the feature that can extend current system by importing new 3D objects. The participants were also asked to perform this virtual experiment to make sure it was workable. Seven out of 9 groups (77% participants) completed the task in 45 minutes with an average completion time 32 minutes. Comparing to time used by computer professionals to create such a virtual environment, 32 minutes can be considered as a short amount of time. This result answered the first research question and provided evidence showing that most average non-technical users of *iVirtualWorld* can create effective virtual experiments with the new feature that enabling the extension of the current system by importing new 3D objects, in a short amount of time. Most of the participants also responded that this feature of *iVirtualWorld* could be used to set up more experiments.

Participants gained their confidence on applying virtual world technologies in education after using *iVirtualWorld*. In addition, they identified the technical barrier as the number one factor preventing the application of virtual worlds in education. Seventy-seven percent participants considered that *iVirtualWorld* could tackle this problem after trying it.

Setting up the virtual experiment using *iVirtualWorld* domain-oriented end-user design interfaces was simple to participants. They could easily finish building the virtual experiment following the instructions. However, they had difficulties conducting the 3D virtual experiment. One possible reason is that most of the participants lacked 3D virtual worlds' experience. The interfaces and operations in 3D space are quite different from that of 2D interfaces. Participants were used to using a mouse to do most of the work. For example, most of the software systems can be operated by clicking on buttons or menu items. However, in 3D virtual worlds, they need to use the keyboard to navigate while holding mouse to move objects. This action seems straightforward and easy for an experienced 3D virtual world player, but it could be frustrated for an amateur. Although the 3D navigation and manipulation skills could be improved by practicing more, as one participant reflected, developers also need to consider improving 3D virtual world interfaces especially for those who are new to 3D space.

5.4 Comparative Case Study[3]

The evaluation studies presented above focused on the usability of *iVirtualWorld* web-based domain-oriented user interfaces. The usefulness of the virtual experiments built by *iVirtualWorld* was assessed by participants using their educational experience. There was a need to better evaluate the virtual experiments generated by *iVirtualWorld* by comparing with other virtual chemistry laboratory systems. A well-developed commercial virtual chemistry laboratory named Virtual ChemLab (Woodfield, 2005) was chosen for a comparative case study with *iVirtualWorld* (IRB number 13X002). The goal of this comparative case study is not to prove that *iVirtualWorld* is better than Virtual ChemLab but rather to explore the differences between these two systems from end-users' points of view. Specifically, this case study was seeking answers to the questions:

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[3] A part of the work described in this section has been submitted as the following paper:
Zhong, Y., & Liu, C. (2013a). A domain-oriented end-user design environment for generating interactive 3D Virtual Chemistry Experiments. *Multimedia Tools and Applications*. (Accepted with required minor revisions)

1) Are the virtual experiments generated by *iVirtualWorld* comparable to Virtual ChemLab experiment?
2) What are the significant differences between *iVirtualWorld* and Virtual ChemLab?

This case study first invited participants to experience *iVirtualWorld* and Virtual ChemLab. Then a semi-structured interview was conducted to elicit participants' perception of these two systems.

5.4.1 Participants

Five participants were recruited for this case study. Among these participants, two were chemistry teachers who had over 30 years' teaching experience but had never used any virtual chemistry simulations in his class before. The rest of the participants were teaching assistants from Biology or Environmental Engineering with less teaching experience. All of them had neither computer programming nor 3D modeling training in the past. Their background validated their representative of the potential users of *iVirtualWorld*.

5.4.2 Procedure

The case study was conducted in a one-on-one mode, i.e. the author worked with one participant at one time. First, the participants were asked to conduct a virtual chemistry experiment in a trial version of Virtual ChemLab following the instructions provided by this system (the permission of using Virtual ChemLab had been granted by its owner). There are several sample experiments available in Virtual ChemLab and the author chose the one that has similar operations as the *iVirtualWorld* TDS experiment, including moving an object, weighing an object, and heating an object.

Next, participants conducted the TDS experiment generated by *iVirtualWorld* with instructions prepared by the author. In this task, there was a difference between the participants. Two participants were provided a link directly to a pre-built TDS experiment and were asked to conduct this virtual experiment. Another three participants were given a task to build a TDS experiment using *iVirtualWorld* and conduct this virtual experiment after building it.

To keep an objective and fair comparison, the possible relationship between the author and any of these two systems was not revealed to the participants. In this case study, the tutorials were not provided to the participants, but the author gave participants helps during the tasks. The author also encouraged the participants to apply "think-aloud" method to speak out their thoughts during their tasks. When the participants finished their tasks, they attended a semi-structured interview with the author to reflect their preference and the reason behind their choice. The questions for the semi-structured interview are:

1) What are the advantages and disadvantages of the first system?

2) What are the advantages and disadvantages of the second system?

3) Which one do you prefer, and why?

4) What improvements are needed for the other one?

During the interview, the researcher presented the *iVirtualWorld* end-user design interfaces to those two participants who did not use them during the task session. The multi-level adaptation was emphasized during the presentation. The researcher planned to observe if there was any change on participants' preference after they were introduced *iVirtualWorld*. The whole case study process, including the tasks finishing and the semi-structured interview, was audio recorded for the analysis.

5.4.3 Results

All participants finished the Virtual ChemLab experiment within 25 minutes with an average time 19 minutes. Two participants completed the Virtual TDS experiment within 15 minutes. The other three participants took average 21 minutes to build and run the Virtual TDS experiment. Because there were no tutorials, participants spent time to familiarize themselves with the operations of two systems during their tasks. The author provided assistances when they encountered difficulties or errors. Their responses to the semi-structured interview are summarized in the following paragraphs.

Overall, all participants considered the *iVirtualWorld* virtual experiments useful for education and comparable to Virtual ChemLab experiments. Participants identified the advantage of Virtual ChemLab is the visual effects. Virtual ChemLab had elegant graphical design and animations and received comments like "*gives you more feel for an actual lab*". Another advantage of Virtual ChemLab is that it provides comprehensive choices of instruments and chemicals for students to choose "*even more than a real-life lab*", which enables numerous combinations of experiments.

As revealed in previous usability study, participants pointed out the same problem of the 3D virtual TDS experiment. That is the navigation and the manipulation of objects in 3D space. However, most participants expressed that they would feel more comfortable of navigation and the manipulation of objects in 3D space if practicing more. One participant without prior virtual world experience reflected that the 2D operations in the Virtual ChemLab were simpler than 3D operations for him. Although the 2D operations did not realistically reflect the 3D movement of objects in the real world, he was more attracted by the realistic graphical design in the Virtual ChemLab than 3D operations in the virtual TDS experiment. This discovery might teach us a lesson: Unless the 3D simulations can be developed as realistic as possible, the operations in 3D space can be complicated, especially for those who have little 3D virtual world experience, and would not please end-users better than 2D simulations with very realistic graphical design. Aesthetic cannot be ignored by 3D virtual world developers.

One participant mentioned that the setting of Virtual ChemLab could be disorienting for students because it involves switching between different scenes. For example, students may need to run back and forth between the stock room scene and the lab room scene several times to obtain required materials for the experiment. Another problem with Virtual ChemLab is that it may take a long time for students to locate required resources in the stock room from a large number of different supplies. One participant had a trouble finding the thermometer needed for the experiment because she did not recognize the thermometer in the stock room. With the help of the researcher, she found the thermometer and moved it from the stock room to the main lab room. A third problem identified by two participants is that students could also be distracted or confused from the current experiment because there are too many different choices to explore, especially for younger students (elementary or middle school students). In some situations, this is an advantage because students have the flexibility to try different experiments. However, for teachers this feature could slow down the progress of a teaching plan. During the interviews with the other three participants, they did not express those observations, but they confirmed these findings when the researcher brought these topics out.

On the other hand, two participants felt that *iVirtualWorld*'s end-user development interfaces are more straightforward. During the task, when one participant saw the interface with inventory, lab bench and settings all in the same page, she spoke out loud that "*this is much better not switching back and forth between different views*", "*I like them all in one page*". Besides, *iVirtualWorld* lets educators choose instruments and chemicals that will present in a virtual experiment. The educators only provide materials needed for one experiment to their students so that students can focus on doing this experiment without being distracted by irrelevant settings. The educators still have the flexibility to add more instruments and chemicals if there is a requirement. According to participants, usually teachers are the ones to prepare for a lab with required instruments and chemicals. Students do not go to the stock room to search for a particular chemical from a large number of supplies. Teachers put required instruments and chemicals on the lab benches before students come to the laboratory to conduct the experiment. From this point of view, *iVirtualWorld* presents a procedure that is more close to the real-life laboratory preparation process, which is more "*intuitive*" and "*straightforward*".

Participants particularly appreciated the adaptation feature of *iVirtualWorld* and considered this feature, especially the extension, was useful. One participant switched her preference from Virtual ChemLab to *iVirtualWorld* after she was introduced to *iVirtualWorld* because of its “customization” functionality. She realized the limitation of the Virtual ChemLab as it has predefined experimental procedure and could be “useless” for teachers to match their lesson plans.

Overall, two participants preferred *iVirtualWorld* while three participants liked Virtual ChemLab better because of its visual effects. The difference is not statistically significant ($p=0.8$). *iVirtualWorld* can be considered as comparable to Virtual ChemLab.

5.4.4 Discussion

The comparative case study of five participants assessed *iVirtualWorld* against a commercial virtual chemistry laboratory system Virtual ChemLab. Participants’ feedback confirmed that the virtual experiments generated by *iVirtualWorld* were considered useful and comparable to Virtual ChemLab experiments. However, participants expected better graphical design and animation implementation in *iVirtualWorld*.

The advantages of *iVirtualWorld* identified in this comparative case study are its straightforwardness, less distraction and customization. The discovery that the solution was more straightforward and less distracting than Virtual ChemLab provides improvement suggestions for related work developing virtual laboratories. Incorporating as many objects as possible in virtual laboratories, as Virtual ChemLab did, can bring rich content to students for conducting virtual experiments. However, students are easy to be confused and distracted facing a large amount of chemistry instruments at once. The effective teaching strategy for educators is to only provide contents that are related to the experiments for their students. Virtual ChemLab will better benefit education if it provides abilities for educators to tailor the system and limit the student view according to specific experiments.

This comparative user study also found that realistic visual effects can be more attractive to end-users than unfamiliar 3D operations, which provides a suggestion for developers in the domain of virtual chemistry experiments. That is, in addition to improvement of 3D operations to better simulate the real world manipulations, developers need to pay attention to the graphical design of the background of environments and objects in the experiments.

5.5 Summary

This chapter presented the evaluation of the proposed domain-oriented end-user development environment in four different phases. The initial prototype *iVirtualWorld* partially implemented the proposed design in the virtual presentation domain including the domain-oriented user interfaces, the parameterization and extension in the multi-level adaptation, the instantiation of 3D virtual environments in concrete virtual world platforms and communication to the concrete virtual world platforms. The evaluation of the initial prototype, containing case studies and a usability study, helped assess the design in an early stage. The results showed that the solution provided average non-technical computer end-users an easy to learn and use virtual learning environment design tool.

Extended from the initial work, a domain-oriented end-user development environment for generating virtual chemistry experiments has been implemented in two phases and evaluated with two usability studies and a comparative case study. The first phase implemented the domain model of the chemistry experiments and modified the domain-oriented user interface to incorporate concepts in this domain model. With the parameterization and integration, end-users could customize certain virtual chemistry experiments using pre-defined domain objects. The first usability study invited domain experts to evaluate this phase's work on learnability, efficiency, effectiveness and satisfaction. Participants reflected that the environment was easy to learn and use. They also confirmed the usefulness of the virtual experiments in certain areas of chemistry, as well as in preparing students with real-life experiments.

The second usability study was designed to evaluate the extension feature added to the system. That is, end-users are able to import new 3D models to *iVirtualWorld* to extend its current inventory. The results showed positive responses to this new feature. This study also investigated participants' awareness and attitudes towards the application of 3D virtual worlds in education. Participants identified the technical barrier as the number one problem preventing the broad application of 3D virtual worlds in education. They considered *iVirtualWorld* as a solution that could tackle this problem. After using *iVirtualWorld*, participants gained confidence on building 3D virtual experiments by themselves.

A comparative case study was conducted to investigate if the virtual experiments generated by end-users using *iVirtualWorld* are at least comparable to a well-developed commercial virtual chemistry laboratory Virtual ChemLab. Participants evaluated that the *iVirtualWorld* experiments were comparable to Virtual ChemLab experiments. The results also discovered the advantages of *iVirtualWorld* over Virtual ChemLab, which are the straightforwardness and less distraction. The customization function, which is the result of the implementation of the multi-level adaptation, was confirmed as useful by participants to create more different experiments.

Overall, the evaluation showed that participants were generally satisfied with the domain-oriented end-user interfaces of *iVirtualWorld*, and they thought it was easy to learn and use. One common problem identified in two usability studies and the comparative case study was the 3D navigation and operations. Participants who had no experience in 3D virtual worlds or 3D games found it difficult to conduct the virtual experiments at beginning. Although end-users could improve their skills through practicing more, developers should also consider how to improve the navigation and manipulation in 3D space for new users. The evaluation also suggested polished artwork in the future, including graphics and animations.

6. Future Work

This chapter discusses future work based on the status of current work and discoveries from the evaluation, which influences future development of the domain-oriented end-user development environment. In addition to the development, further evaluations are also needed to comprehensively assess the solution.

6.1 Future Design and Development

This dissertation employed domain-specific modeling technology to analyze the chemistry experimental education domain and designed a domain model as a blueprint for developers to design and develop domain-oriented end-user interfaces with domain-specific languages. The chemistry experimental education domain contains a huge number of concepts that could not be entirely covered in this dissertation. The work in this dissertation intended to prove the solution using a small portion of concepts in chemistry experimental education domain. Future design is necessary to extend the current domain model by incorporating a comprehensive range of domain-oriented concepts.

The adaptation is a fundamental feature of this solution to enable end-users to build and modify 3D virtual experiments. Current implementation of three levels of adaptation provides certain flexibility to end-users. With the extension of the domain model, more domain-oriented concepts will be covered, which also requires future work on adaptation implementation. On the parameterization level, more concepts will bring more attributes and behaviors for end-users to configure. On the integration level, more concepts results in more interactions that need to be implemented between them. On the extension level, future work needs to provide functionalities for end-users to import 3D objects from different resources other than Google Warehouse. This may require further development to convert other types of 3D model files to the types of files acceptable by Unity3D or other virtual world platforms.

The design of this domain-oriented end-user development environment is capable to export the virtual worlds to more than one virtual world platform, which has been proved by the initial work for virtual presentations. Currently *iVirtualWorld* only builds virtual experiments on the Unity3D platform. The future work of the system includes instantiating the domain-oriented language in other virtual world platforms, running on desktops, laptops, or even mobile devices. The game engine Unity3D has the ability to export one web player project to a mobile device such as iPhone/iPad, or Android device, with a certain amount of changes. This advantage will be taken to enable building 3D virtual chemistry experiments for mobile devices. Other web-based virtual world platforms without plug-in installation could also be a good direction to explore.

The evaluation revealed a common problem in several studies, i.e., users without 3D virtual world experience found it difficult to navigate and manipulate in 3D space at the beginning. Although participants' skills were improved after practicing, the researchers may need to study the possibility of improving the navigation and manipulation in 3D space for new users.

6.2 Further Evaluation

The evaluation so far has focused on the *iVirtualWorld* website part because the scope of this dissertation is the domain-oriented end-user interfaces. Domain experts have been recruited to evaluate the usability of *iVirtualWorld*, especially the domain-oriented end-user development interfaces. Although domain experts considered that the virtual experiments created using *iVirtualWorld* were useful, the actual effects need to be assessed in classroom settings. One of the future works should be the classroom assessment.

The comparative case study presented in Section 5.4 discovered a possible causal-effect relation between *iVirtualWorld*'s domain-oriented end-user development interfaces and end-users' preference to *iVirtualWorld* over other comparable virtual chemistry experiments systems. There was no sufficient data to support this relation in that case study. A comparative study involving a large sample size of participants could be designed to test this hypothesis in the future, which could further explore the impact of such a domain-oriented end-user development tool on end-users and chemistry educational domain.

7. Summary

This last chapter concludes the work presented in this dissertation and highlights the contributions of this work to related research areas.

7.1 Conclusions

In this dissertation, a solution for a domain-oriented end-user development environment was developed to ease the creation of 3D virtual chemistry experiments for educators by employing end-user development technologies such as domain-specific modeling and multiple level adaptations. A prototype, *iVirtualWorld*, was implemented in two phases. In phase one, domain-oriented design interfaces and the first two levels of the adaptations (parameterization and integration) were developed. In phase two, the extension feature and the third level of the adaptation were implemented. Evaluation through usability studies and case studies was conducted on *iVirtualWorld*, with a focus on how the domain-oriented interfaces influence the creation of 3D virtual chemistry experiments. All 14 participants in the phase one usability study and 14 out of 18 participants in the phase two usability study finished building a virtual experiment within one hour, which is much faster than using a generic virtual world building tool to create a similar virtual experiment. All 14 participants of the phase one usability study and 8 out of 13 participants of the phase two usability study responded that the layout of the domain-oriented interfaces was easy to understand. The domain-oriented interfaces were considered easy to learn as confirmed by over 90% of the participants in the phase one study and 70% of the participants in the phase two study. Over 75% of the participants in the phase one study agreed that parameterization could be used to create more experiments and over 90% of the participants realized the usefulness of the extension ability of bringing new concepts for building more experiments. Participants in both usability studies gained confidence in applying 3D virtual world technologies in education. A comparative case study further revealed that the solution was comparable to a commercial system and was more straightforward and less distracting. The results of the evaluations show that applying end-user development technologies on 3D virtual worlds enables average non-technical computer end-users like educators to build 3D virtual educational environments, especially virtual chemistry experiments, easily and quickly. Multi-level adaptation increases the flexibility to create more virtual experiments. End-users gained confidence on applying 3D virtual world technologies, which will broaden the usage of 3D virtual worlds in education.

7.2 Contributions

The main contributions of this dissertation are in the following areas: Virtual Educational Environments, End-User Development, Domain-Modeling in Chemistry Domain and Empirical Studies. This section describes these contributions in detail.

7.2.1 An Easy Way to Build Virtual Educational Environments for Non-Technical End-Users

In this dissertation, an innovative solution was developed to ease the building and manipulating of 3D virtual educational environments, especially virtual chemistry experiments, for non-technical computer end-users, particularly educators, using 3D virtual worlds. The evaluation showed that the average computer end-users, without programming and 3D modeling skills, were able to create workable and useful 3D virtual chemistry experiments in a short amount of time. Educators who attended the evaluation gained confidence on applying 3D virtual worlds in education after learning the solution, which will encourage them to consider incorporating 3D virtual world technologies in their teaching through the solution provided in this dissertation.

7.2.2 The Application of EUD to the Virtual Chemistry Experiment Domain

This dissertation extends the application of EUD technologies to the field of 3D virtual chemistry experiments development by non-technical end-users, particularly educators. By hiding underlying computer science details using domain-oriented design, the solution devised in this dissertation presents end-user interfaces with graphical building blocks representing the chemistry experiments domain-oriented language elements, which are easier to learn and use for non-technical end-users (e.g. educators) in the domain than traditional 3D virtual world building tools. The user studies showed that end-users were able to build virtual chemistry experiments in a short amount of time. Participants responded that the solution was easy to learn with its easy to understand interfaces.

This dissertation applied EUD three-level adaptation (parameterization, integration, and extension) to provide end-users the abilities to create, modify and extend virtual chemistry experiments, making it possible for non-technical educators to develop virtual chemistry experiments without programming or 3D modeling technologies. Participants in the user studies tested and confirmed the adaptation functionalities for customizing virtual chemistry experiments.

This dissertation analyzed chemistry experimental education domain. Inspired by the domain-specific modeling technology in EUD, a domain model of chemistry experiments has been established in Section 3.1.1 and been applied to the implementation of the domain-oriented end-user development environment in Section 4.2.2. This work not only provides practical experience of domain-specific modeling but also contributes a domain model with its implementation in chemistry experimental education domain.

7.2.3 Technical Contributions

This study made technical contributions to facilitate the application of EUD in the domain of virtual chemistry experiments. For example, the Unity3D Collision Detection mechanism was employed to implement the integration adaptation. This dissertation also contributed a 3D object conversion pipeline to realize the extension adaptation, using the automation mechanism and the conversion functionalities of Google SketchUp and Autodesk FBXConvertor.

This dissertation applied Unity3D automated building mechanism to automatically compile the Unity3D project and deliver the executable virtual experiments to end-users. Dynamical loading of 3D objects at runtime was implemented so that only objects chosen by end-users for a virtual experiment are rendered when the virtual experiment is launched, ensuring the customization ability of the solution presented in this dissertation.

End-user design interfaces and the three-level adaptation in virtual chemistry experiment domain were implemented using dynamic web page technologies, providing end-users a web-based application that is flexible to access without installation and update needs while keeping rich user-computer interactions similar to standalone computer programs.

Those technical contributions have been tested in the user studies. The fact that end-users could successfully build their virtual chemistry experiments confirmed the effectiveness of the technical implementations.

7.2.4 Empirical Evidence

Empirical studies involving various methods, including controlled task completion, think-aloud, semi-structured interviews, and case studies, were conducted to evaluate the solution. Quantitative and qualitative data was collected through research instruments including background surveys, timing measurements, post-task questionnaires, observations, and interviews. Twenty-eight out of 32 (88%) participants of the usability studies were able to build a 3D virtual chemistry experiment within one hour using the EUD tool prototype developed in this dissertation. The solution was evaluated as easy to learn by 80% of the participants and easy to use by 52% of the participants. More than 70% of the participants considered that the solution could tackle the technical barrier problem faced by educators when learning and using 3D virtual worlds. The comparative case study revealed that the solution was more straightforward and less distracting than a commercial system.

The finding from the comparative case study provides guidance for related work on virtual laboratories. Incorporating as many objects as possible in virtual laboratories can bring rich content to students for conducting virtual experiments. However, more content presenting to students at once would distract them from the major purpose of learning a specific topic. From the point of view of educators, the effective teaching strategy is to only provide contents that are related to the teaching objectives to their students. Virtual laboratories will benefit education better if they provide abilities for educators to tailor the system according to specific experiments.

Another lesson learned from the evaluation showed that the operations in 3D space can be complicated and would attract end-users less than realistic graphical design in 2D space, especially for users with little 3D virtual world experience. Developers in the virtual chemistry experiment domain need to improve the 3D operations, as well as pay special attention to the aesthetic of the 3D virtual world environments.

Evidence extracted from the empirical data proves the effectiveness of applying EUD technologies in 3D virtual world building. This dissertation contributes practical experience of applying different empirical study methods in the areas of EUD and virtual educational environments. The results of the work provide empirical data for evaluating the usability of EUD tools and studying target audience, i.e. educators, on their awareness of and attitudes towards application of 3D virtual world technologies in education.

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Appendix A Questionnaires

A.1 Phase One Usability Study (As Distributed to Participants)

A.1.1 Background Survey

1. Gender: __Male __Female

2. How long have you worked as a chemistry teachers or lab instructors?

__ < 1 year __ 1-3 years __3-5 years __>5 years __other________________

3. Please tell us about your computer programming experience?

__ < 1 year __ 1-3 years __3-5 years __>5 years __other________________

4. Please tell us about your 3D virtual world experience?

__ < 1 year __ 1-3 years __3-5 years __>5 years __other________________

5. Please check all the virtual worlds you have ever used.

__ Second Life __ OpenSim __Unity 3D __Active Worlds __Open Wonderland __Twinity __Kaneva __Smallworlds __other________________

6. I think 3D virtual world technologies are useful in education?

__ Strongly agree __ Agree __ Neutral __ Disagree __ Strongly disagree

7. How do you think the possibility to create a 3D virtual experiment by yourself?

__It is impossible. Creating a 3D virtual experiment is very difficult for me and I do not have time and energy to learn it.

__It is possible. Creating a 3D virtual experiment is difficult for me but I can learn it if I have to.

__It is practical because creating a 3D virtual experiment is easy for me.

__Other____________________________________

A.1.2 Questionnaires

Five points Likert-Scale questions (from Strongly disagree to Strongly agree):

1. I do not need extra trainings about 3D modeling technologies to create a 3D virtual experiment using *iVirtualWorld*

2. I do not need extra trainings about computer programming skills to create a 3D virtual experiment using *iVirtualWorld*

3. Overall, I think *iVirtualWorld* is easy to learn

4. The layout of "creating virtual experiment" web page is designed in a way that I can easily understand

5. It is easy to design the virtual TDS experiment using *iVirtualWorld* by reading the experiment description provided

6. Designing a virtual experiment using items in the inventory provided by *iVirtualWorld* is similar to designing a real experiment

7. I feel comfortable to use *iVirtualWorld*

8. The system gave error messages that clearly told me how to fix problems (optional)

9. I can easily finish my task with my knowledge of chemistry (e.g. TDS) by using *iVirtualWorld*

10. The ability of changing instruments' settings can help me create different experiments as I wish

11. Overall, I can easily build a virtual TDS experiment using *iVirtualWorld*

12. The process of creating a 3D virtual experiment in *iVirtualWorld* is designed in an efficient way so that I can build 3D virtual experiments in short time

13. Creating a 3D virtual experiment using *iVirtualWorld* cost less time than preparing a physical experiment

14. Creating a 3D virtual experiment using *iVirtualWorld* is more economical than preparing a physical experiment

15. Creating a 3D virtual experiment using *iVirtualWorld* is safer than preparing a physical experiment

16. Creating a 3D virtual experiment using *iVirtualWorld* is convenient because I can do it anytime and anywhere with a computer and Internet

17. I would find *iVirtualWorld* useful for Chemistry teachers

18. Overall, I am satisfied with *iVirtualWorld*

19. Overall, I think *iVirtualWorld* is easy to use

20. Three-dimensional virtual world technologies are useful in education

Yes/No questions:

1. During my task, I had no trouble to identify an instrument from the inventory by looking at the small icon.

__ Yes __ No

2. During my task, I had to look at the large icon to identify at least one instrument.

__ Yes __ No

3. During my task, I had to look at the name under the small icon to identify at least one instrument.

__ Yes __ No

4. During my task, I knew what instruments from the inventory do I need to build the virtual experiment.

__ Yes __ No

Open-ended questions:

1. Will you recommend *iVirtualWorld* to a Chemistry teacher? Why?

__ Yes __ No __ Not sure

2. Will you use *iVirtualWorld* for your class if possible? Why?

__ Yes __ No __ Not sure

3. How do you think the possibility of creating a 3D virtual experiment by yourself after you attended this user study? Why?

__It is possible. Creating a 3D virtual experiment is easy for me using *iVirtualWorld*.

__It is impossible. Creating a 3D virtual experiment is still difficult for me even using *iVirtualWorld*.

4. Do you have any comments for this user study?

A.2 Phase Two Usability Study (As Distributed to Participants)

A.2.1 Background Survey

1. Gender: __Male __Female

2. What subjects are you teaching now? (What subjects are you helping teaching if you are a fellow?)

__ Math __ Science (chemistry or biology) __ Science (not chemistry and biology) __ Other (specify here ________________________________)

3. How long have you been teaching/helping teaching this subject?

__ 0 year __ < 1 year __ 1-3 years __3-5 years __>5 years

__other_______________

4. Have you ever teach chemistry or biology before if you are not teaching them right now? And for how long?

__ 0 year __ < 1 year __ 1-3 years __3-5 years __>5 years

__other_______________

5. Please tell us about your computer programming experience?

__ 0 year __ < 1 year __ 1-3 years __3-5 years __>5 years

__other_______________

6. Please tell us about your 3D virtual world experience?

__ 0 year __ < 1 year __ 1-3 years __3-5 years __>5 years

__other_______________

7. Please check all the virtual worlds you have ever used. (Leave them blank if you have no virtual world experience.)

__ Second Life __ OpenSim __Unity 3D __Active Worlds __Open Wonderland

__Twinity __Kaneva __Smallworlds __other_______________

8. How did you use virtual worlds? (Leave them blank if you have no virtual world experience.)

__ I just walked around inside it.

__ I played games inside it.

__ I built objects inside it.

__ other ____

9. I think 3D virtual world technologies are useful in education?

__ Strongly agree __ Agree __ Neutral __ Disagree __ Strongly disagree

10. Have you ever considered using virtual world technologies in your class?

__ I have never thought about this because I do not think they are useful for education.

__ I have thought about this but they are difficult to use because it needs computer science related skills to use them.

__ I am currently applying virtual world technologies in my class.

__ other ______________________________________

11. What reasons below could prevent virtual world from being used in education in your opinion? (Select all applicable.)

__ Educators may face technical barriers when learning and using virtual worlds.

__ The educational materials are insufficient in virtual worlds.

__ Virtual worlds have inappropriate content for students.

__ other _____________________________________

12. How do you think the possibility to create a 3D virtual experiment by yourself?

__It is impossible. Creating a 3D virtual experiment is very difficult for me.

__It is possible. Creating a 3D virtual experiment is easy for me.

__other______________________________________

13. How do you think the possibility to learn to use virtual world technologies in order to use them in your class?

__ It is impossible. I do not have time and energy to learn it.

__ It is possible. I can learn it if I have to.

__ I am already very good at it so I do not need to learn it.

__ other ______________________________________

A.2.2 Questionnaires

Five points Likert-Scale questions (from Strongly disagree to Strongly agree):

1. I do not need extra trainings about 3D modeling technologies to create a 3D virtual experiment using *iVirtualWorld*

2. I do not need extra trainings about computer programming skills to create a 3D virtual experiment using *iVirtualWorld*

3. The layout of "creating virtual experiment" web page is designed in a way that I can easily understand

4. Overall, I think *iVirtualWorld* is easy to learn

5. Setting up a virtual experiment using items in the inventory provided by *iVirtualWorld* is similar to what a teacher does in real life

6. I feel comfortable using *iVirtualWorld*

7. I can easily finish my tasks with my current knowledge background by using *iVirtualWorld*

8. The ability of adding new instruments to *iVirtualWorld* is useful for setting up more experiments

9. I can easily build a virtual Dissolved Oxygen experiment using *iVirtualWorld*

10. I can easily build another virtual experiment using *iVirtualWorld (optional)*

11. The process of creating a 3D virtual experiment in *iVirtualWorld* is designed in an efficient way so that I can build 3D virtual experiments in short time

12. Setting up 3D virtual experiments using *iVirtualWorld* costs less time than preparing similar physical experiments

13. Setting up 3D virtual experiments using *iVirtualWorld* is more economical than preparing similar physical experiments

14. Setting up 3D virtual experiments using *iVirtualWorld* is safer than preparing similar physical experiments

15. Setting up 3D virtual experiments using *iVirtualWorld* is convenient because I can do it anytime and anywhere with a computer with Internet access.

16. I find *iVirtualWorld* useful for Chemistry or Biology teachers.

17. Overall, I am satisfied with *iVirtualWorld.*

18. Overall, I think *iVirtualWorld* is easy to use.

Multiple-choice and open-ended questions:

1. After trying *iVirtualWorld*, do you think if it is possible to apply virtual world technologies in education?

__ I think this can be useful for education.

__ I still do not think they are useful for education.

2. What problems below can be tackled by *iVirtualWorld* from your opinion?

__ Educators face technical barriers when learning and using virtual worlds.

__ The educational materials are insufficient in virtual worlds.

__ Virtual worlds contains inappropriate content for students.

__ Other ____________________________________

3. Would you recommend *iVirtualWorld* to other Chemistry/Biology teachers? Why?

__ Yes __ No __ Not sure

4. Will you use *iVirtualWorld* for your class if possible? Why?

__ Yes __ No __ Not sure

5. How do you think the possibility of creating a 3D virtual experiment by yourself after you attended this user study? Why?

__It is possible. Creating a 3D virtual experiment is easy for me using *iVirtualWorld*.

__It is impossible. Creating a 3D virtual experiment is still difficult for me even using *iVirtualWorld*.

6. Do you have any comments for this user study?

Appendix B Usability Study Tasks

B.1 Phase 1 Usability Study Task Description (As Distributed to Participants)

In this task, you are going to design and build a 3D virtual experiment called Total Dissolved Solids (TDS) using *iVirtualWorld* according to below description:

1. Weigh an empty beaker (W_b) using a balance.
2. Transfer 1ml unknown solution into the beaker using an autopipette.
3. Weigh the beaker with solution (W_{bs}).
4. Heat the beaker with solution with a Bunsen burner.
5. When the water of the solution is vaporized, weigh the beaker with residue (W_{br}).
6. Calculate the TDS of this unknown solution using below formula:

$$TDS(\%) = \frac{W_{br} - W_b}{W_{bs} - W_b} \times 100$$

You can design and build your 3D virtual experiment following below steps:

1. Click "Create a New World" button to enter the virtual world building web page. In this task, a "virtual world" means a "virtual experiment". You can start building your TDS experiment.
    a. Give a name to your virtual world and a brief description
    b. Find out lab instruments and chemicals needed for your experiment from "Inventory" tab on the left of the screen, drag-and-drop them onto the virtual desktop in the center of the screen, and provide parameters for the settings on the right of the screen.
    c. When you are satisfied with your organization of the virtual experiment, click "Build" button to build it.

2. If the virtual experiment is built successfully, you will be provided a link to the virtual experiment. Click that link and try the virtual experiment created by you.
3. If you want to do some changes, you can go back to *iVirtualWorld* website's "My Worlds" web page, find your virtual experiment from the list, click "edit" link to edit it and rebuild it. Rebuilding a virtual experiment will be faster than first building.

Once you are satisfied with your virtual experiment, you are done with this task.

B.2 Phase 2 Usability Study Task Description (As Distributed to Participants)

Suppose you are going to teach students the topic about water quality of Ohio River this semester. Dissolved Oxygen (DO) is an important parameter indicating the water quality. The Winkler Method is a popular method to test the Dissolved Oxygen of water samples. Your school has bought Lamotte Dissolved Oxygen kits, which applies the Winkler Method. Your students will conduct hands-on experiments in your class using these kits to test the Dissolved Oxygen using water sample collected from Ohio River. However, the number of kits are limited and not enough for every student to perform the Dissolved Oxygen testing process, which means that several students have to share one set of kit.

You hope that students learn this method better and conduct the experiment more efficiently, so you decided to design a virtual Dissolved Oxygen experiment that is very similar to the one using the Lamotte Dissolved Oxygen kits. With this virtual experiment, your students would get familiar with the kit and the procedure prior to the class and practice more after the class if they want to. The tool you are going to use to design the virtual Dissolved Oxygen experiment is called *iVirtualWorld*, which is a web application providing chemical components for teachers to prepare virtual chemistry experiments according to their requirements. You have been trained with the basic information of *iVirtualWorld*. Now it's time for you to practice it.

Below is the description of the procedure of the Winkler Method using Lamotte Dissolved Oxygen kit for your reference. (Note: During the task you will notice that the "*squeeze bottle*" is not provided by default by *iVirtualWorld*. You will need to go to http://sketchup.google.com/3dwarehouse/ to search for that 3d model and upload it to *iVirtualWorld*.)

1. Get a bottle brim-full with sample water.
2. Add 8 drops of manganese sulfate to the bottle.
3. Add 8 drops of alkali-iodide-azide to the bottle.
4. Mix the sample by inverting several times. If oxygen is present, a brownish-orange cloud of precipitate will appear. Allow the precipitate to settle to the shoulder of the bottle.
5. Add 8 drops of sulfuric acid to the sample water. Invert several times to dissolve the precipitate. At this point, the sample is "fixed".
6. Pour 20ml fixed sample water into a titration sampling bottle.
7. Fill titration syringe with 1 ml sodium thiosulfate.
8. Add 1 drop of sodium thiosulfate at a time, swirling between each drop until the sample becomes white yellow.
9. Add 8 drops of starch indicator solution so a blue color forms.
10. Continue slowly *titrating* until the sample turns clear.

The concentration of dissolved oxygen in the sample is equivalent to the number of milliliters of sodium thiosulfate used. Every 0.1 mL of sodium thiosulfate is equivalent to 1ppm DO, or 1mg DO per 1L of water. For example, 1.4 ml of sodium thiosulfate = 14 ppm DO (14 mg DO per L).

Appendix C An XML File of a Virtual TDS Experiment


```xml
<world>
 <id>143</id>
 <name>My TDS Experiment</name>
 <desc>Total Dissolved Solids</desc>
 <objects>
  <object>
   <id>2584</id>
   <name>Beaker</name>
   <path>http://vitallab.dyndns-
server.com/~vital/iVirtualWorld/websitetest/upload/beaker_small.obj</path>
   <position>
    <x>23.1667</x>
    <y>42.6316</y>
   </position>
   <properties>
    <property>
     <id>1</id>
     <name>Can it be moved around by users?</name>
     <value>true</value>
     </property>
    <property>
     <id>3</id>
     <name>How much does it weigh?</name>
     <value>100</value>
    </property>
   </properties>
  </object>
  <object>
   <id>2587</id>
   <name>Autopipette</name>
   <path>http://vitallab.dyndns-
server.com/~vital/iVirtualWorld/websitetest/worlds/vital_13/143/assetbundles/autopipette.unity3d</pat
h>
   <position>
    <x>61</x>
    <y>40.5263</y>
   </position>
   <properties>
    <property>
     <id>1</id>
     <name>Can it be moved around by users?</name>
     <value>true</value>
    </property>
    <property>
     <id>2</id>
     <name>Can it be rotated by users?</name>
     <value>true</value>
    </property>
   </properties>
  </object>
```

```
    <object>
      <id>2589</id>
      <name>Balance</name>
      <path>http://vitallab.dyndns-
server.com/~vital/iVirtualWorld/websitetest/upload/balance.obj</path>
      <position>
        <x>42.8333</x>
        <y>41.8421</y>
      </position>
      <properties/>
    </object>
    <object>
      <id>2590</id>
      <name>Bunsen burner with frame</name>
      <path>http://vitallab.dyndns-
server.com/~vital/iVirtualWorld/websitetest/upload/bunsenburnerframe.obj</path>
      <position>
        <x>9.66667</x>
        <y>41.3158</y>
      </position>
      <properties/>
    </object>
    <object>
      <id>2591</id>
      <name>Solution</name>
      <path>http://vitallab.dyndns-server.com/~vital/iVirtualWorld/websitetest/upload/jar.obj</path>
      <position>
        <x>78.8333</x>
        <y>42.8947</y>
      </position>
      <properties>
        <property>
          <id>4</id>
          <name>Chemical name</name>
          <value>Salt water</value>
        </property>
        <property>
          <id>5</id>
          <name>Total dissolved solids (TDS)</name>
          <value>39000</value>
        </property>
        <property>
          <id>6</id>
          <name>Density</name>
          <value>1.025</value>
        </property>
      </properties>
    </object>
  </objects>
</world>
```

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