The Future of Research in Computer Games and Virtual Worlds

The Future of Research in Computer Games and Virtual World Environments:

*Workshop Report**

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July 2012

Prepared for National Science Foundation grant #1041918, starting from the *2010 Workshop on the Future of Research and Challenges in Computer Games and Virtual Worlds*

*** Citation and online version of this Report***:*

Scacchi, W. (Ed.), (2012). The Future of Research in Computer Games and Virtual Worlds: Workshop Report, Technical Report UCI-ISR-12-8, Institute for Software Research, University of California, Irvine, Irvine, CA. July 2012.
http://www.isr.uci.edu/tech_reports/UCI-ISR-12-8.pdf

Executive Summary

More than 30 scholars engaged in research on topics related to Computer Games and Virtual Worlds (CGVWs) participated in a workshop to identify future research problems and opportunities in this arena. Six working group topics were identified based on the scholarship and interests of the invited participants. The groups were then tasked to meet, discuss, and debate their respective topics, the results of which appear as the first six chapters of this report. The six CGVW chapter topics are:

- *Computer Systems Technologies for CGVWs*—multi-core and many core processors, computer graphics hardware and software, networking, databases, language design, sensors, etc.
- *Advanced GGVW Technologies*—AI, behavioral scripting, narrative and emergent systems, procedural and non-procedural content generation, avatar generation and customization, world building kits, etc.
- *Media, Art, Culture and History of CGVWs*—CGVWs as media, art, literature and expressive forms of social critique; new literacies, creativity with or through CGVW, etc.
- *Anthropological, Behavioral, Sociological Studies of CGVWs*—ethnographic studies of CGVWs, work-versus-play or work-as-play or play-as-work, patterns of migration across CGVWs, CGVW in complex enterprise settings, research methods for studying CGVWs.
- *Education and Learning with CGVWs*—how CGVW sfacilitate or inhibit learning in formal or informal education settings, play as learning, CGVWs for STEM and Humanities learning, etc.
- *CGVWs for Science, Health, Environment, Energy, Defense—C*GVWs as research tools or infrastructure for R&D in other scientific, industrial, or government domains, etc.

Each chapter addresses a common set of concerns including current research findings, emerging research problems of high consequence, future research infrastructure needs, and broader impacts arising from research investments in each of the six topic areas.

Contributors to these chapters represent a diverse set of scholars and disciplines that might not otherwise be drawn together. No effort was directed to integrating the results presented across the chapters, so each chapter can be read and reviewed standalone, though better if reviewed comparatively across chapters.

The report also identifies overall observations that advocate investment in future CGVW research. Their intent is to be bold and stimulating. These observations are summarized as follows.

CGVWs as new media and technologies of practice have the potential to pervade most, if not all, sectors of scientific research, technology development, educational and cultural practices in industry, academia, and government. CGVWs are not a “killer app,” but instead *CGVWs are more likely the next Web*: a new layer of systems and applications that can cross social, organizational, institutional and technological boundaries, just like the World-Wide Web has done over the past 15 or so years.

CGVWs are not about mere “gamification” by which we mean turning existing socio-technical systems into those where users simply earn virtual badges, points, or prizes for accomplished game play. Instead, CGVWs are rich socio-technical systems that can facilitate creativity, new cultural practices, new educational opportunities, and new ways and means for stimulating research and higher education in the sciences, health, and related disciplines.

CGVWs are embracing the next-generation workforce of those who will seek to work in the various MACH, SHEED, ABS, and advanced IT disciplines, industries or government agencies. Market research figures suggest that at least one billion people world-wide are now playing and interacting through CGVWs. Investments in STEM education do not yet address this, nor do current R&D investments across government agencies identify this situation.

The U.S. currently leads the global development of new CGVW-centered products and services. Such socio-economic condition and market leadership can be accelerated through investment in a new CGVW research agenda, such as that identified in this report. New firms and highly skilled jobs will emerge through such investments into CGVW research, as can new markets.

Future research in CGVWs can be targeted to different research agencies and research programs that can maximize interests through targeted investments. Games for health care represents one such application domain for focused CGVW research. Games for health may be able to provide a new way and means for facilitating self-managed chronic care ailments that can be personally rewarding as well as transformative—not in the sense of curing the ailment, but in the sense of making the ailment amenable to personal activity and self-care more manageable.

Research in CGVWs overlaps most areas of current interest that advance the overall science research agenda for networked information technology (NITRD 2012). Massively multi-user CGVWs represent new venues for communication and social interaction that generate big data about social, behavioral, cultural, and technological practice, all data that characterize societal processes. New research challenge problems like reanimating the visible human can generate new scientific knowledge from domains that link or converge across nanotechnology, biology, information technology, and cognitive science (NBIC) disciplines.

The industries currently vested in CGVWs as entertainment media are not leading the way in pushing the R&D horizons identified in this report. Without coordination of research investment, CGVW technology will emerge as disjoint, islands of automation that will become evermore complex and costly to integrate for mutual benefit.

This report identified six related areas that would benefit from strategic or programmatic R&D investments. The national NITRD (2012) agenda and grand challenge problem domains are both amenable to be favorably advanced through investment in CGVW research. In particular, the NITRD Program and this report put forward recommendations for a planning and coordination support request whose structure provides a model for what, where, how, when, and why to invest in to strategically stimulate CGVW research (NITRD 2012, pp. 19-20): *Co-funding* testbeds, infrastructures, and advanced tools/instrumentation for experimentation with new CGVW technologies; *Workshops* that mobilize and bring together researchers, program managers, and socio-economic leaders; *Collaborative deployment* of new CGVW system infrastructures, tools, repositories/archives across R&D programs; *Interagency cooperation* to focus research investment that identify and provide solutions to challenges in mission-oriented SHEED programs; *Technical standards* for interoperable, scalable, secure, and scalable CGVW systems and infrastructures; *Testbeds* that enable the joint R&D experimentation, crowdsourcing, and decentralized study of CGVWs; and a S*cience and Technology Steering Council*.

Overall, CGVWs are an engine of innovation: one that can stimulate the production of new knowledge and practice in multiple scientific, creative, cultural, educational and IT-centered disciplines, industries, and government agencies. CGVWs are emerging as socio-technical ecosystems for addressing problems in areas such as education, socio-economic development, health care, and scientific research. This statement is based not on speculation, but on diverse R&D results, projects, and expertise cited in this report and beyond (see Steinkuehler Squire 2011). CGVWs represent transformative technologies and socio-economic practices whose time is coming, and whose opportunity to strategically invest is near at hand. If the purpose of careful and cautious investment of limited public funds is to realize the greatest benefits to many diverse public and private interests, then CGVW merits serious attention, consideration, and commitment of resources that can fuel this engine of innovation. Such engines of growth and prosperity are uncommon and often elusive. Keep this new engine of innovation well fueled and fund its improvement.

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Preface: Workshop goals, process, and contributors

Walt Scacchi and Magda El Zarki

The Center for Computer Games and Virtual Worlds (CGVW) at UC Irvine hosted a National Science Foundation funded workshop on advancing the agenda for research and education in CGVW environments during September 2010. The Workshop brought together 30-40 participants drawn from computer science, film/media arts, social sciences, education and humanities. The over-arching aim was to craft a research agenda and future directions for research and educational programs for CGVW environments. Structured as a research summit, this event engaged participants in an interdisciplinary dialog on the creative, social, technical, educational, and businesses challenges posed by the “beyond-the-next generation” of CGVW. Work on contributing to the refinement, evolution, and completion of this report continued until July 2012. The report is thus nearly two years in the making.

This Workshop brought together the community of researchers and scholars interested in these problem areas. Our goal was to elicit, capture, and document what this community finds are the critical needs and grand challenges that help articulate a national research agenda on CGVW going forward over the next 5-10 years. The Workshop solicited and collected online position papers from the participants to start our discourse and debate. Subsequently, the Workshop participants were asked to contribute to the production of a final report intended for dissemination both to interested researchers and program directors in the Computer and Information Science and Engineering (CISE); Social, Behavioral, and Economics (SBE); Education and Human Resources (EHR); other research agencies and industrial research centers, and other related communities. Thus, our overall goal was to raise awareness and identify an agenda for action for relevant research communities as to critical research problems and challenges that are emerging around the science, technology, engineering, and education/learning for CGVWs.

More than 30 scholars engaged in research on topics related to the development, use, and evolution of CGVWs agreed to participate in this Workshop. Each invited participant was given the opportunity to give a presentation up to 5 minutes at the beginning of the Workshop to present their research interests, findings, and problem areas for further study. These initial presentations were open to the public.

Six working group topics were identified based on the scholarship and interests of the invited participants. These CGVW topics include:

- *Computer Systems Technologies for CGVWs*—multi-core and many core processors, computer graphics hardware and software, networking, databases, language design, sensors, etc. Group lead, Mic Bowman, Intel.
- *Advanced GGVW Technologies*—AI, behavioral scripting, narrative and emergent systems, procedural and non-procedural content generation, avatar generation and customization, world building kits, etc. Group lead, Michael Mateas, UC Santa Cruz.
- *Media, Art, Culture and History of CGVWs*—CGVWs as media, art, literature and expressive forms of social critique; new literacies, creativity with or through CGVW, etc. Group lead, Noah Waldrip-Fruin, UC Santa Cruz.

- *Anthropological, Behavioral, Sociological Studies of CGVWs*—ethnographic studies of CGVWs, work-versus-play or work-as-play or play-as-work, patterns of migration across CGVWs, CGVW in complex enterprise settings, research methods for studying CGVWs, etc. Group lead, Bonnie Nardi, UC Irvine.
- *Education and Learning with CGVWs*—how CGVW sfacilitate or inhibit learning in formal or informal education settings, play as learning, CGVWs for STEM and Humanities learning, etc. Group lead, Betty Hayes, Arizona State University.
- *CGVWs for Science, Health, Environment, Energy, Defense—C*GVWs as research tools or infrastructure for R&D in other scientific, industrial, or government domains, etc. Group lead, Walt Scacchi, UC Irvine.

Each participant was asked to participate in one of these Working Groups at the Workshop, and contribute to discussion, scholarly debate, report preparation and briefing of the Working Group results. Each Working Group had a designated leader to help initiate discussion, but each group could self-select who they want to make the final presentations, and to help lead in the production of a Working Group report. Consequently, each Working Group was expected to produce a report and brief presentations that document the results or outcomes from their discussion. Their reports constitute the major chapters of this report and follow in turn in the order identified above.

Each Working Group was given the same task for their respective area of interest in CSVW: produce a paper (a chapter in this report) that: (a) introduces and briefly characterizes the topic area, (b) identifies and describes representative research problems that will drive the creation of new scientific knowledge in the area, (c) outlines future research infrastructure that can more rapidly advance science and technology breakthroughs in the area, and (d) identifies broader impacts that help signify the value of research in the area. Each Group then elected how best to address their task, the result of which are documented and described in the six chapters that follow. After the Working Group reports were collected, compiled and edited together into draft version of this report, it was then shared for iterative review and revision by the contributors, who could then also identify changes in other chapters. So each Working Group report identifies its primary authors, while "others" as secondary contributors refer to Workshop participants who provided improvements (additional details, references, example screenshots, etc.) across chapters. However, no effort was directed to integrating the results presented in each chapter, so each can be read and reviewed standalone, though better if reviewed comparatively across chapters.

Beyond this, a final chapter is included which summarizes and discusses major findings or observations that underlie the range of research across the diverse disciplines of the contributing scholars to this report. This last chapter also provides a set of recommendations for consideration by those in the broader scientific research community who may act to fund and stimulate the multiple lines of research that can drive the creation of new scientific knowledge and stimulate socio-technical innovation through future computer games and virtual worlds.

Overall, it should be clear that these six chapters should not be construed as covering all aspects of CGVW research. This report is the result of the efforts of the contributors who represent distinct yet robust communities of interest. Other CGVW topics ***not*** addressed and thus missing in this report include:

- the psychological, cognitive, and neurological aspects of play, learning, and interaction within CGVWs;
- the economics of CGVWs and the economic systems that empower or mediate interactive play in different large-scale CGVWs;
- comparative analysis of different game genres, and the communities of developers and players who embrace them;
- cross-cultural studies of CGVWs that draw attention to emerging market opportunities on a global basis, and the provision/denial of access to diverse ethnic or socio-economic communities of players.
- review of existing government research programs contributing support to different CGVW research projects, either within the U.S. or on an international basis.

Finally, it is also important to note that CGVWs are not a panacea: they are not conceived nor intended to resolve societal challenges by themselves. However, they do represent a new media and new technology that allow us to begin to address, discuss, and play with such challenges in ways that may be fun, sociable, competitive, and stimulating. The capabilities of CGVWs outlined in this report may thus begin to point to new ways and means for engaging, discussing, debating, and exploring these challenges.

Contributors

This report is the result of a workshop held from 23-24 September 2010 at the Center for Computer Games and Virtual Worlds in the Donald Bren School of Information and Computer Sciences, University of California, Irvine regarding the future of research in computer games and virtual worlds. The workshop was organized by Magda El Zarki, Computer Science Department, and Walt Scacchi, Institute for Software Research, both at the University of California, Irvine. The report reflects the input from thirty or so workshop participants, listed below, from the research community, including academia, industry, and members of the open source community:

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Acknowledgements

Finally, a report of this volume and complexity requires the support and contribution from a community, in addition to the Working Group contributors. They are acknowledged here.

First, the *2010 Workshop on the Future of Research and Challenges in Computer Games and Virtual Worlds, 23-24 September* 2010, was supported by a grant #1041918 from the National Science Foundation. Additional funding was provided by the Office of Research, the Donald Bren School of Information and Computer Sciences, and the Institute for Software Research, all at UCI. No review, approval, or endorsement is implied.

Second, support for workshop contributors Scacchi, Kanomata, Lopes, Nardi, Nies, and others at the UCI Institute for Software Research was also provided in part from the National Science Foundation grant #0808783. No review, approval, or endorsement is implied.

Third, administrative support for the workshop came from Debra Brodbeck and Kiana Fallah. Technical and Web services support came from Yuzo Kanomata and Kari Nies. Debra Brodbeck also assisted in the final production and publication logistics for getting this report completed. All are from the Institute for Software Research at the University of California, Irvine.

Fourth, Venita De Souza formerly at the Donald Bren School for Information and Computer Sciences also played a strategic, administrative, and financial management role in facilitating the success of the Workshop and local arrangements.

Last, the great cover art for this report was created by Alex Szeto, Institute for Software Research.

Without the timely consideration, attention, and extraordinary effort provided by these people, the Workshop and Report could not have been successfully organized, performed, and completed. Their efforts are greatly appreciated.

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1. Computer Systems Research for CGVWs

Mic Bowman (Lead), Magda El Zarki, Wu-Chang Feng, Mike Freedman, Huaiyu (Kitty) Liu, Cristina Lopes, Gregor Schiele, Walker White

Introduction

The commercial popularity of various forms of computer games and virtual worlds, including Massive Multi-player Online Games (MMOG) and Massive Multi-player Virtual Environments (MMVE), has created a very stable, mature understanding of CGVW technologies. However, radical changes in both the technological, social and business environment antiquate much of what we know about CGVW technologies.

Changes in technology open the doors to richer, more realistic and immersive environments. The emergence of new computing platforms based on highly parallel, many-core processors for both graphics and general-purpose computing open the door to dramatic improvements in simulation and visualization. Communication bandwidth continues to grow rapidly enabling more dynamic, real-time interaction. Further, games and virtual worlds are accessed from increasingly diverse computers spanning low-power mobile platforms to high end gaming platforms.

The emergence of social applications like Twitter and Facebook change the social expectations as well. People expect to interact richly with people in entertainment, social and business settings. And with more interactions taking place through game-like technologies, the potential for abuse increases.

Economic factors are driving other changes. Within the game industry, the move to sales of digital objects as a means of revenue generation causes game currencies to have real value. Cheating now has the potential for considerable economic impact. In addition, with increasing awareness of environmental impact and the rising cost of travel, companies are looking for alternatives that are more financially and environmentally sound.

Each of these trends puts pressure on traditional game technologies. It is our belief that we need “revolutionary” advances to address the opportunities and problems that arise. What follows is a summary of the main research problems related to the computer systems that support these rich environments.

Research Problems

The research problems of interest in the domain of CGVW systems include scalability, security, software engineering, multi-platform delivery, interoperability and federation. Each is described in turn.

Scalability

Goal: To deliver “orders of magnitude” scalability improvements in terms of number of concurrent users, content complexity and fidelity of experience.

As is often the case, the limitations of system architectures greatly influence uses of the platforms. MMVE and MMOG platforms have been architected for “scale out”. That is, it is relatively easy to support more and more users by adding “space” over which users can be spread. However, existing software architectures are unable to “scale up” to greater interactions among the users and fail to handle significant increases in the visual and behavioral complexity.

Research problems

We believe there are at least three dimensions of scalability that must be addressed:

- The number of concurrent users interacting with each other.
- Content complexity, captured by the number of objects in a scene and the complexity of their behaviors and appearance.
- The fidelity of user interactions.

Current findings and their limitations

The first dimension is to scale the number of concurrent users interacting with each other. Current virtual worlds have to split the user base and restrict interactions to achieve scalability. For instance, Second Life applies static space partitioning to decompose the space into 256m x 256m regions, each handled by one server. *World of Warcraft* uses *sharding*: a part of the virtual world is replicated into shards and different shards reside on different servers, but users on different shards are isolated from each other. Both approaches degrade the user experience: sharding prevents large groups of users from interacting and static partitioned regions collapse with too many users (Erikson et al 2011, Gupta at al. 2009).

The second dimension is to scale content complexity, captured by the number of objects in a scene and the complexity of their behaviors and appearance. For example, standing on a street corner in a real city and looking as far as possible, one could observe a massive number of objects in sight. For example, people are walking and talking, a street musician is playing, the traffic lights are changing, a driver honks his horn, and the wind is blowing leaves and bits of paper along the sidewalk. In the virtual world, each object consists of a structural representation model, shading and texture information, physical information such as mass and density, and scripts which control their behavior and interactions with other objects. The precise behaviors and interactions must be simulated and communicated to the client, and rendered onto a display. As the number of objects in increases, or as the complexity of their behaviors or appearances increases, so do the computation, communication, and rendering requirements. Traditionally in games, the scene is pre-created by game designers and pre-distributed, for instance, by CDs. Yet that requires client machines to have powerful compute and rendering capabilities at runtime and does not support a diverse range of client platforms. It also limits the scene complexity to only what has been pre-designed. Recent approaches such as OnLive® use remote rendering and media streaming in order to support high content complexity to diverse client platforms, yet it still faces challenges such as very limited number of concurrent users and long lags in game plays.

Scale the content complexity is especially challenging in general purpose virtual worlds where user-generated content is dominant. Users can build objects with a potentially infinite set of behaviors, hence the term “general purpose”. When a scene becomes more complex, the demand for computation, communication, and rendering can quickly overwhelm the whole system. For example, a complex scene such as the Shengri La Chamomile region on

ScienceSim (ScienceSim 2010 – see Figure 1) has 256K objects (billions of triangles), yet it was observed that user experience degraded at around 35K objects (FRI blog 2010).

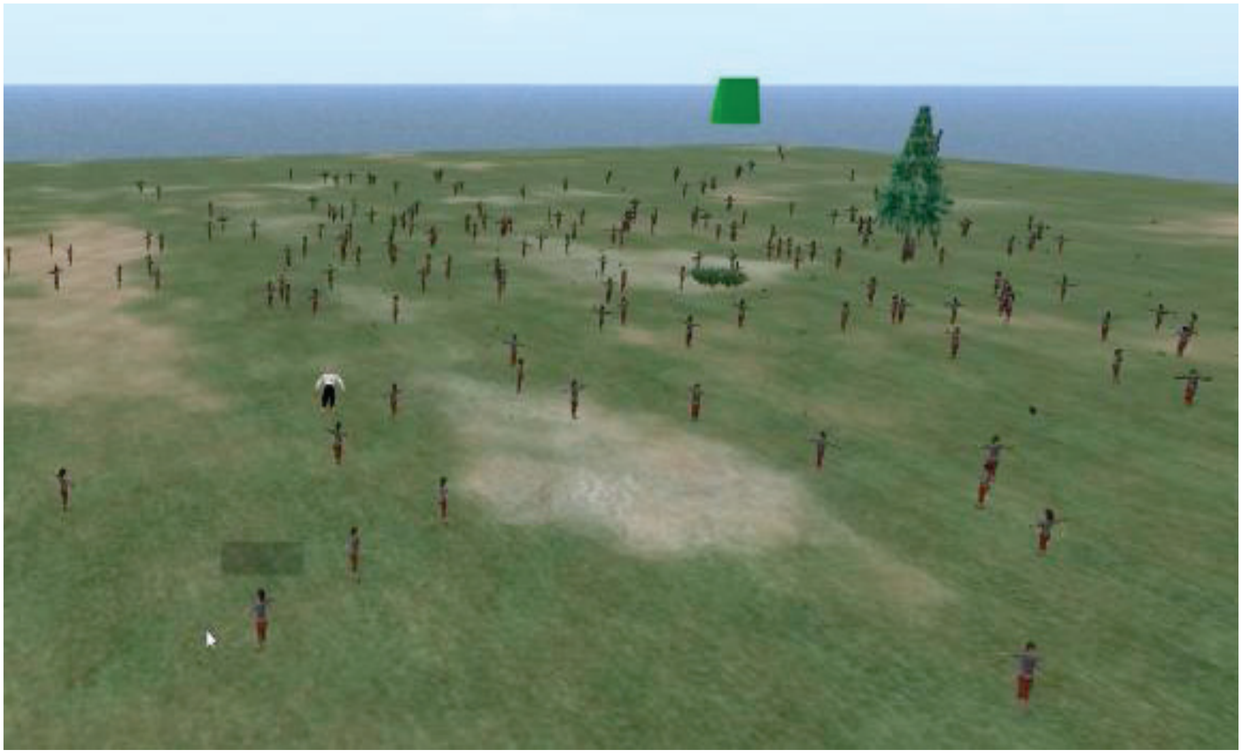

Figure 1. A scene from *ScienceSim* displaying some of the 1000 concurrent in-world avatars that can be supported using Intel's Distributed Scene Graph cluster processing (Lake, Bowman, Liu, 2010).

The third dimension is to scale the fidelity of user interactions. In current virtual worlds, user interaction is usually very simple and occurs within a limited range: avatars or objects can only interact with others within a small distance in the same region or shard (Horn et al. 2010). On the other hand, users demand rich experiences and the ability to express a large number of interactions with different complexity, granularity, and scope. Further, they want to interact in a broad range, for example, coordinating with others to do “the wave” virtually in the stands of a virtual soccer arena. Enabling high fidelity interaction requires improvements and innovations in user interfaces. The challenges, however, go beyond user interfaces. For example, user actions are generally unpredictable and it is hard to apply techniques such as dead-reckoning (Singhal & Zyda 1999) to reduce the bandwidth for sending updates to users. Innovative solutions in addressing the enormous demands for computation and communication need to be developed to support high fidelity interactions.

Security

Goal: To prevent cheating and malicious attacks.

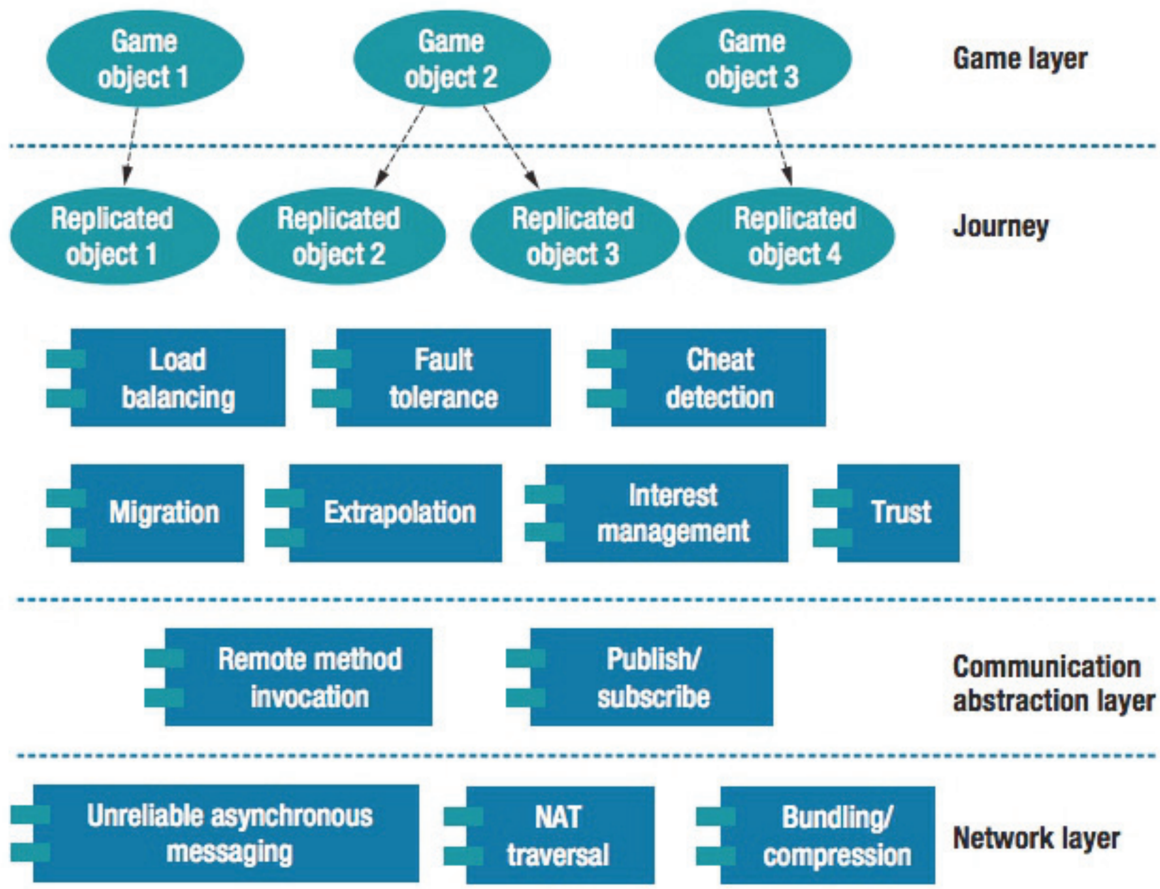

Figure 2. A scalable multi-layered middleware abstraction supporting large numbers of concurrent users and game objects (Denault and Kienzie 2011).

Cheating and malicious attacks threaten the existence of all networked CGVWs. Unfortunately, much like the Internet was initially designed without security in mind, most CGVWs and games are designed without considering potential adversaries.

Over the last decade, as CGVWs and games have become more important and profitable to users, attacks against them have become more common and sophisticated. For example, several cheats for games employ advanced techniques found in malware such as: modifying critical application files, injecting code and data into the running application process, and attaching itself as an external process to the application to hijack execution. In addition, cheats employ polymorphism (Jacob et al. 2009, NTkrnl Packer), metamorphism (Szor 2006), code obfuscation (PreEmptive Solutions), and anti-debugging methods (Windows, Russinovich 2009, Ebringer 2008) to prevent the application provider from understanding and detecting them. There is one significant difference that makes protecting CGVWs and games from attack more difficult: the adversary owns the machine the software is running on.

As a result of this, the malicious code typically runs with administrator privileges and can completely avoid detection from anti-cheat software running in user-space by hiding underneath the game within the kernel (Hoglund 2006, Glider). With this in mind, solving the cheating problem will help solve the general malware problem.

Current findings

There is significant work in the area of malware detection. Anti-malware software takes a defense-in-depth approach that employs both signature-based detection of known malware, as well as anomaly-based detection of unwanted behaviors in well-known applications. Such software searches within the file system, every application process, every operating system service, and the operating system kernel itself for potential compromise. In addition, they employ large libraries of code signatures generated by experts as well as run-time behavior analysis of code in an attempt to identify compromises (Kaiser 2009, Forrest 1996, Idika & Mathur 2007).

Research problems

There is one assumption anti-malware software makes that is essential to its correct operation: the owner of the machine wants to detect and remove the malicious software.

Unfortunately, the above methods only work when the owner of the machine is willing to run them. In on-line CGVWs, the owner of the machine seeks to actively prevent and disable any software that attempts to infect or corrupt it. Thus, the overall goal in advancing security in this problem area is to develop new approaches that it make it much more difficult and costly for an attacker to compromise or corrupt the CGVW application. Some of the open research problems in this area include:

- designing methods and building tools and methods that ensure and verify the proper execution of application code at all times;
- designing network protocols that are resistant to compromise from malicious attack at the end-point and in the network;
- adapting the application design and the delivery of sensitive data based on how trusted a client is;
- on-line transformation of application software to actively break cheat software; and
- methods for making the development of cheats and malicious software prohibitively more expensive.

Software Engineering

Goal: To decrease the time and cost of producing, maintaining and evolving these environments by orders of magnitude.

Research problems

We believe these environments challenge the state of the art in Software Engineering in at least three dimensions: tool chain, expressive and extension, and software system architecture.

Tool Chain

An inordinate amount of the time and expense in game development is spent towards content creation and asset management. Content creators often have little or no programming experience, and so the programmers have to create a content creation pipeline of tools to integrate their work into the final product. These tools take assets produced by the content creators using their domain specific programs (e.g. a 3D modeling program such as *3D Studio Max*, a digital composition program such as *Logic*, or a composed mashup of tools as a software development kit (SDK) such as *Unreal Development Kit*) and transforms them into a data format suitable for the game engine.

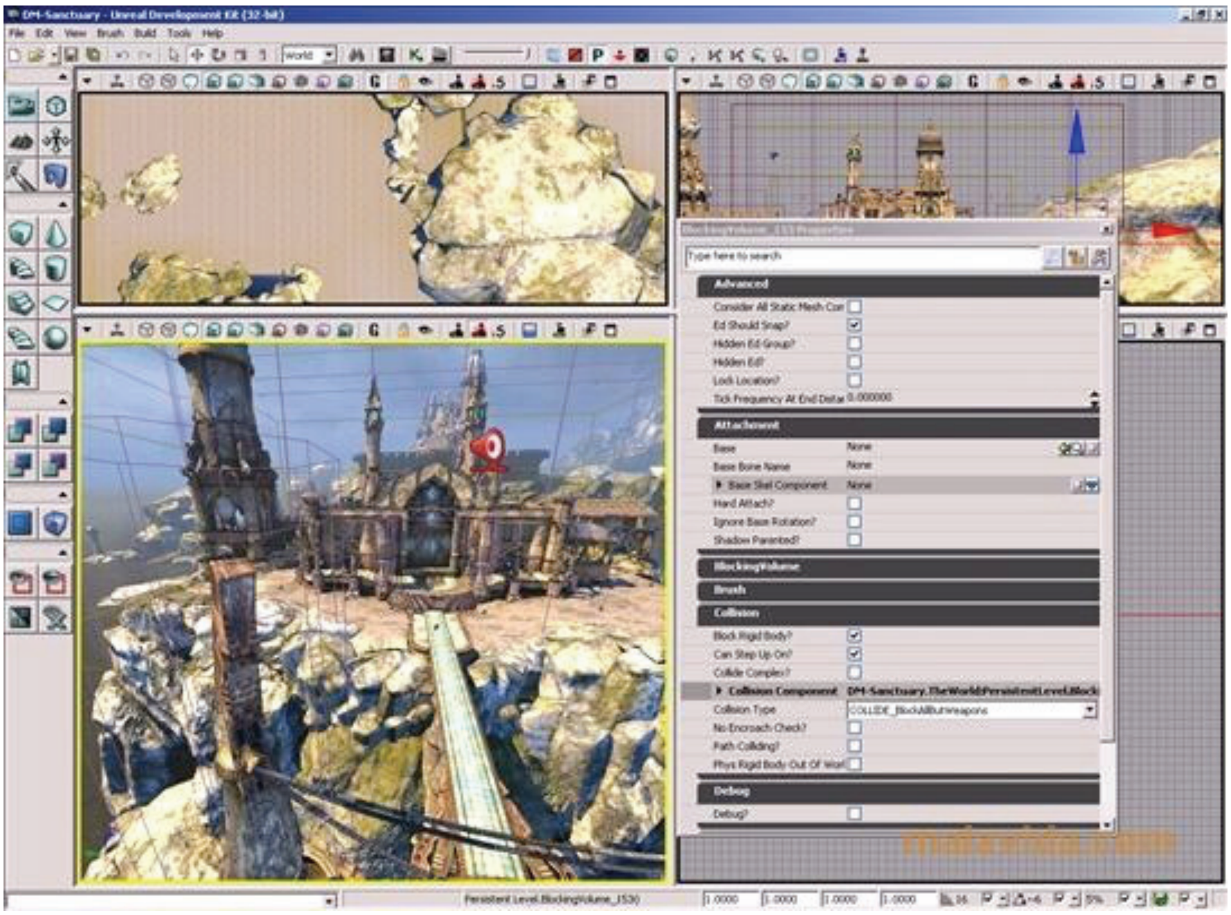

Figure 3. Screenshot of the *Unreal Development Kit*, displaying different tools (e.g., object property editor, object viewer, world viewer) running in different windows

These content creation pipelines can become quite large and complex. There are many types of game content - art assets, music and sound effects, dialogue, character behavior, and a separate pipeline must be created for each. In some cases, content in the pipeline goes through several stages before it reaches the game engine; for example, one artist may make a 3D character model, and then pass this to another artist to develop hairstyles or clothing.

Unfortunately, in addition to being quite complex, these pipelines are extremely brittle. Designers regularly add and remove attributes from the game objects as they tune the gameplay, even long after the game has been released. This alters the underlying data format, making it incompatible with the output of the content creation pipelines. Hence these changes have to be propagated throughout the pipeline. For example, simply adding a new attribute to a game character requires changes in the database schema, the (database) stored procedure calls, the network protocol, the character creation tools, and so on. As a result, such changes are a massive undertaking, and game studios spend an enormous amount of time and money dealing with this issue. Indeed, many of their solutions are ad-hoc and result in bugs as different parts of the system have different versions of the data model.

In order to solve this problem, we need to develop an intelligent content creation pipeline. This pipeline must provide developers with the freedom and expressiveness to design a wide range of game features; it must also adapt to these changes in design, modifying the various pipeline components appropriately. Additionally, this pipeline must be tightly coupled with the software for the game engine; changes in the content creation tools must generate new software code for the engine, and changes to the game engine should be reflected in the content tools.

Currently game designers rely on scripting languages to give them a restricted version of this functionality. These languages allow designers to specify how an object or character is supposed to behave, without worrying about how to integrate this behavior into the game itself. This integration happens automatically, either through code generation or a script interpreter embedded in the game engine. These languages are particularly important for massively multiplayer games, where any piece of code must interact with multiple subsystems, from the application layer to the networking layer to the database.

However, this approach is still very limiting. These scripting languages only integrate with game engines and not the other content creation tools. Furthermore, the bridge between the scripts and the game engine is often game-design dependent; while the designer can make modest changes to the game through the scripts, major changes require significant modification of the game engine.

We foresee several research opportunities regarding the content-creation pipeline. The first and foremost is the development of new software engineering principles for designing game behavior. A formal framework will allow us to understand how the various pieces of the pipeline fit together, and how changes in design should propagate throughout.

Expressiveness and Extension

We need to develop languages that allow designers to be creative and expressive, but also take advantage of formal software engineering principles to integrate their work automatically. As such, domain-specific scripting languages are another important area of research. By leveraging unique features of game architecture, these languages may provide several opportunities for performance optimization, such as automatic parallelization, distribution, or special-purpose data structures.

There are also opportunities for game-specific refactoring analysis. When a developer makes changes to the game engine -- which is written in a traditional programming language -- we must detect those changes that affect the content pipeline, and handle them appropriately. The algorithms developed may detect these changes with various degrees of accuracy, and either update the pipeline automatically or make recommendations to the developer accordingly.

Last, computer game “mods” are a primary example of software extensibility mechanisms at work and play that can be further investigated and applied in new applications. Game mods extend the core functionality of a game. Many games now are delivered to end-users with an open access software development kit (SDK) that allows the end-user the means to modify various aspects of the look, feel, rules, and play experience of a game. Extensions also support the creation of entirely new games that cannot be readily anticipated from the delivered game through “total conversion” modding methods. Common extension mechanisms rely of the use of scripting languages (or domain-specific languages) that can be created and manipulated through the SDK in order to access and modify the assets/contents of the original game (Scacchi 2011). However, modding and mod-based software extension is not well understood from a research standpoint, and thus merits attention as to how develop and apply a new generation of modding tools and techniques, including meta-modding tools (Scacchi 2010).

Software System Architectures

Architectural choices determine: the game system infrastructure; whether a particular technology or component can be added to the game (modularity); and the possibility to adapt and extend to evolving requirements and constraints (flexibility and extensibility).

Mostly focusing on scalability, current trends evolve around Peer-to-Peer (P2P) architectures (Assiotis & Fan 2006) and hybrids of P2P and traditional client-server (Jardine & Zappala 2008). Some architectures promote a publish/subscribe approach (Fielder 2002). Other architectures have focused on specific metrics such as latency in mobile gaming (Khan, et al. 2010) to design their system.

Other architectural designs for games could come from the software architecture and software engineering community. For instance, based on the REST principles, CREST (Erenkrantz et al. 2007) takes into consideration the computations happening on the Internet and could be a valuable architectural design for games.

Multi-Platform Delivery

Goal: To deliver rich, interactive 3D content on platforms that are well-integrated with people’s everyday computing activities.

Today, the generic Web browser, mobile devices, and dedicated consoles are the primary user-facing platforms for content delivery. However, delivering rich 3D content over these platforms poses several challenges that must be solved in order to make this content well-integrated with everyday computing activities.

Research problems

We believe there are three directions to be explored in order for this kind of content to become routine: improving abstract graphics APIs; incorporating virtual machines that are able to adapt to specific graphics hardware; and decreasing the overhead of server-side rendering technology.

Current findings and their limitations

Dedicated consoles are the choice of preference for highly immersive games, but they have many disadvantages for scientific and educational applications. Namely, these consoles are standalone hardware that isn’t well-integrated with the processes and tools that most people use routinely. These consoles have emerged for dealing with the hard technical challenges of 3D immersive content delivery on everyday hardware/software platforms, which only recently started to take these kinds of applications into account. Indeed, delivering highly 3D immersive environments on laptop computers and mobile platforms poses substantial software engineering and programming languages challenges.

These applications have computationally intensive graphics that must achieve ultimate performance from whatever hardware they run on. Given the variety of hardware in people's computers and mobile phones, producing these applications usually involves having to manually optimize the end-user programs in many different ways. Not just memory management and parallelism need to be optimized, but for mobile platforms battery usage needs to be taken in to account too. As a consequence of the software engineering complexity coming from having to maintain many optimized components, many content producers limit the end-user delivery software to only 1 or 2 platforms (e.g. Windows only or iPhone only). This problem is seriously hampering wide accessibility to these applications. If immersive 3D environments are to become embedded in everyday computational activities, the problems associated with delivering these environments to end users must be solved.

Three approaches are emerging for dealing with these problems: (1) abstract graphics APIs; (2) virtual machines; and (3) server-side rendering, resulting in video being delivered to end-users. With respect to abstract graphics APIs, HTML5 introduced WebGL, a 3D graphics API based on OpenGL and implemented in web browsers without the use of plug-ins. While this is a promising approach, the performance of WebGL is still far from acceptable for rendering rich 3D scenes. The problem with the abstract API approach is that it hides away all the important features of graphics cards that allow the performance optimizations. The challenge here is to be able to take advantage of the specific hardware without having to write programs for multiple APIs. With respect to virtual machines, they also suffer from the same problem of abstracting away the important local features of the hardware. Moreover virtual machines that run natively on the Web browser need to enforce security. With respect to server-side rendering, this is a promising approach that would simply eliminate the complexities of client-side rendering. The problem with server-side rendering is that it requires a massive amount of computation and bandwidth on the server-side; although some online games are starting to use this, the technology is far from the point of being ready for general use.

Interoperability and Federation

Goal: To decentralize authority, so that innovation can flourish.

For all their benefits and popularity, today's virtual environments (VE) and worlds are characterized by centralized control and administration. All physical resources and administrative controls are managed by a single entity, e.g., Blizzard for *World of Warcraft* or Linden Labs for *Second Life*. No interaction is possible between users in these walled-garden virtual environments, limiting the "network effect" of such technologies, and innovation is constrained by the system's central operators.

The success of the Internet as a disruptive technology---and all the subsequent technologies that use it as a communications platform---arguably arose from its ability to knock-down previously walled-gardens by its embrace of interoperability and federation. The main task of the early Arpanet was connecting local networks running disjoint protocols into a common internetwork (or Internet). The World Wide Web as an application service hosted on the Internet allowed users to easily post, read, and organize content, linking content that may be physically hosted at distant servers. In the U.S. at least, the Internet finally became a widespread phenomenon when online portals such as CompuServe, Prodigy, and America Online finally provided access to the public Web, newsgroups, and IRC channels. More recently, the same phenomenon is happening with federating social networks (e.g., through the OpenSocial directive) and online authentication (e.g., through OpenID).

We believe that the same federation and interoperation that enabled the wide-spread growth of and innovation on the Internet is necessary for virtual environments. Such a world could link together different managed environments, could enable end-users to host their own environments or use a platform provided by a service provider, and could provide a common programmatic environment for creating and developing virtual objects.

There are different visions about what such federation and interoperability may entail, and we expound on the realm of possibilities below. At its limits, federation and interoperability provide the same type of seamless experience that one experiences on much of the current World Wide Web, where content, code, and service is readily shared, users quickly flit between providers, and the platform provides the flexibility, programmability, and deployability needed to quickly innovate and grow, and disruptive lock-in can be minimized.

At its ultimate, the virtual world ecosystem must be able to support large numbers of CGVWs with very different uses and administrative properties. At the same time, many service providers---from large commercial entities to single-server hosting sites---may contribute computational, networking, and storage resources to run these virtual worlds. To enable a seamless virtual universe rather than walled-garden networks, these different physical and administrative domains must be able to cooperate and interoperate while simultaneously maintaining internal control of their network operations. For such a network to provide ease-of-use, performance, availability, and reliability, objects and environments must not be physically tied to a single server or domain; users (avatars) and objects must be able to move across worlds for seamless integration, with movements being controlled by a mix of provider and user requirements. At the same time, all involved parties---including users, application developers, world administrators, and service providers---need to be able to protect themselves from malicious entities and influence some system decisions and control.

Alternative architectures for realizing a virtual ecosystem range from the distributed grid of virtual world “island” servers originally found in *Second Life* (Rosedale and Ondrejka 2003) to the contemporary choices being explored in *Open Wonderland* (Kaplan and Yankelovich 2011) and *Unity* (Katz, Cook, and Smart 2011) approach that build on current Web application architectures, to the *OpenSim Hypergrid* (Lopes 2011) which extends and federates the grid model underlying Second Life. Each of these three alternative architectures provides a different framing for how to scale in a decentralized manner in ways that provide different compatibility and implementation strategies. Figures 4,5 and 6 help to visualize how these architectures differ in their composition and services provided.

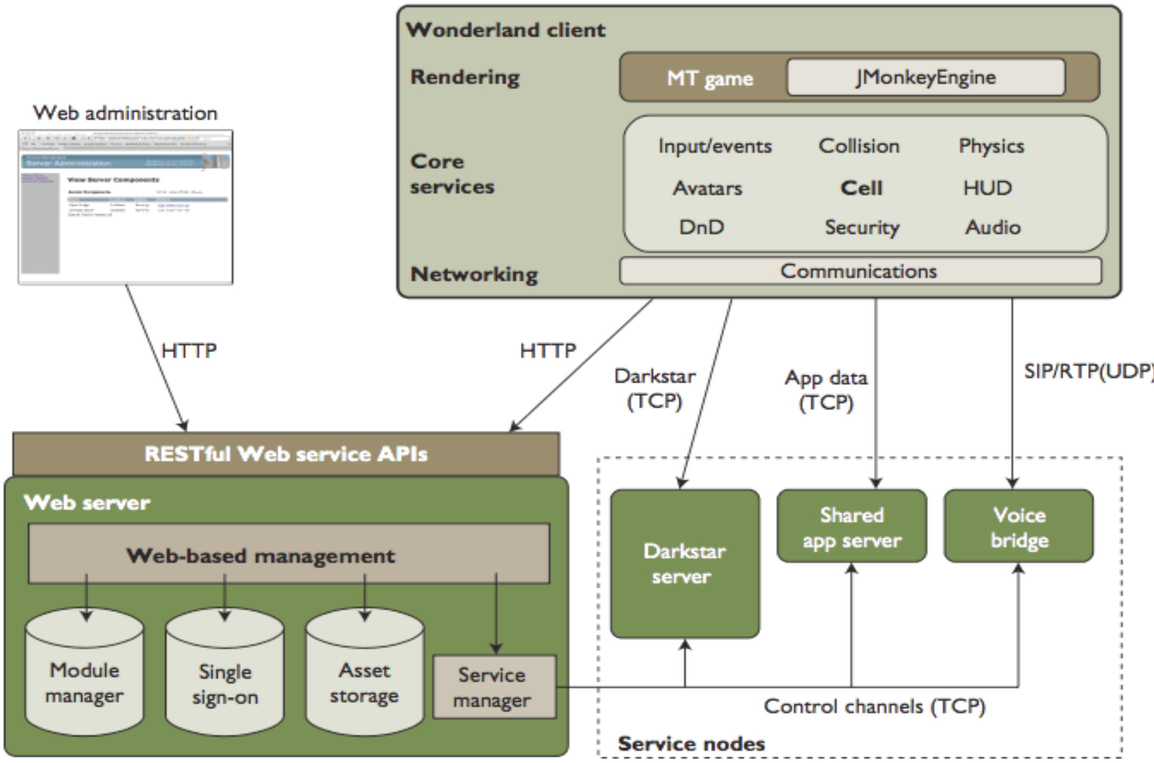

Figure 4. Web-compatible architecture used in *Open Wonderland* (Kaplan and Yankelovich 2011).

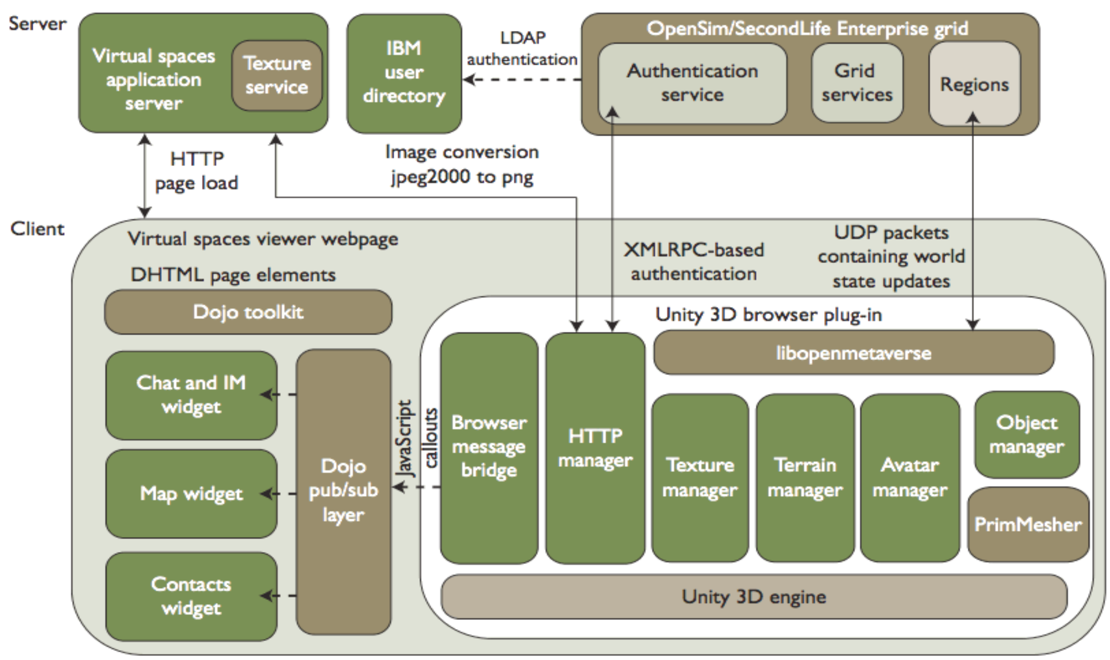

Figure 5. Web-compatible architecture for embedding the *Unity 3D* application player within a common web browser (Katz, Cook, Smart 2011).

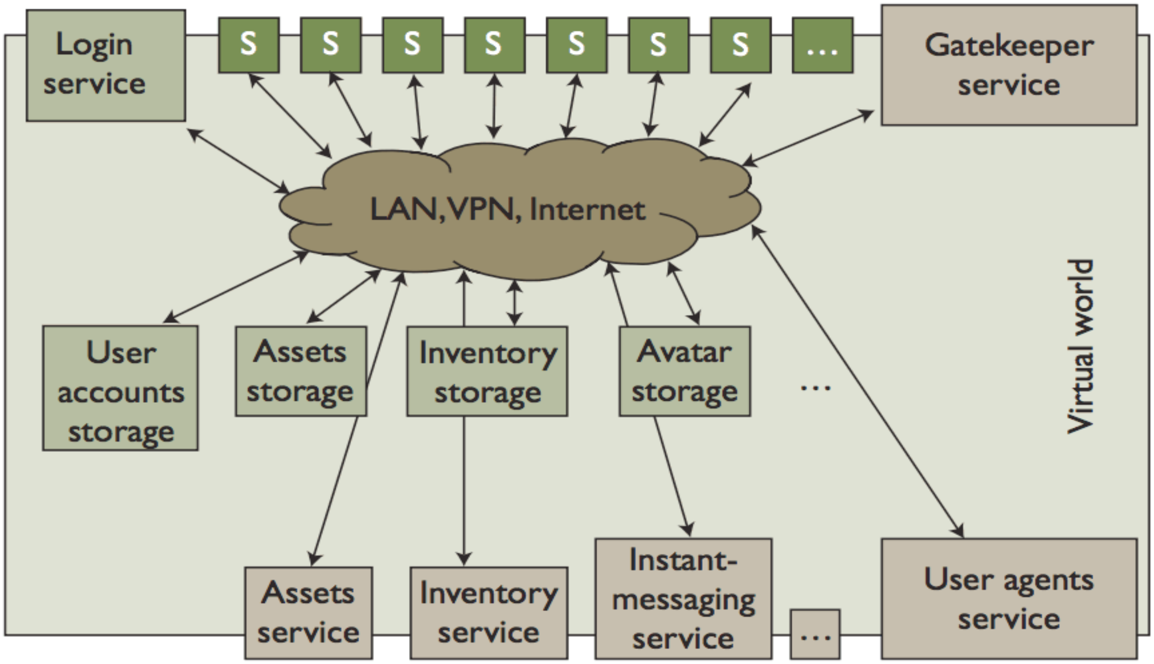

Figure 6. The Second Life compatible OpenSim Hypergrid architecture enabling interoperability and scaling across OpenSim-based virtual worlds (Lopes 2011).

The differences and similarities among these architectural alternatives points to the need for further study to better understand whether they can be converged, whether the problems they address can be unified, or whether they must all co-exist due to the lack of interoperability standards.

Research problems

Towards this end, there are several intermediate steps one might take, which we next summarize in their order of complexity:

- Permanent import/export between different providers: As a user may permanently move from one provider or another, they should be able to take their avatar, objects, and other local state and export it to another user or different CGVW. VWs are no different, yet certainly offer significantly more technical challenges, as the functionality and representation between VWs may differ significantly, so interoperability challenges are still impractical to resolve. Tools to automate such interoperability, as well as architectural designs that many providers will adopt to better enable such functionality, will certainly help.
- Temporary execution in a different setting: While the previous example considered the permanent move of a user's state, a federated environment might see the desire to temporarily join a separate virtual world. Two researchers at different universities who seek to collaborate, for example, might choose one of their universities' virtual environments to temporarily coexist in. Similarly, a CG player might seek to temporarily try out other massive multiplayer online game environments, yet keep much of the work that she has already done to personalize her avatar, and so would like to see basic

functionality, appearance, behavior, etc. be automatically imported into the other environment.

- Federated durability and storage resources: Once multiple providers are operating virtual environments that a user wishes to move between -- whether or not the underlying code/platform for these environments is identical, or whether some type of interoperability import/export is needed -- we still have to worry about how we manage object state. When a user sojourns to a different environment, we need to worry about how and where state changes happen. Some in-world information may reside on other platforms, other information might be pulled back to a user's own dedicated storage service. Beyond traditional performance, consistency, and fault-tolerance concerns, this problem introduces questions about data format interoperability and common programming APIs.
- Federated execution and computational resources: Certain environments may be larger than any one provider, or providers may wish to give the sense of a more seamless experience between worlds. (If two virtual regions are connected to create the appearance of a seamless space, major events in one region, such as a huge explosion, may want to be visually seen or heard by another.) Such an experience again requires standardization or interoperability of communication APIs and message-passing interfaces.
- Support for heterogeneous platforms and environments: Finally, interoperability between environments is related critically to capabilities and functionality offered by these environments or the platforms (both server- and user-side) on which they run. One environment and platform might support an immersive and rich experience (in turns of visual, audio, etc. input/output to users), running expensive computational and communication tasks (e.g., using back-end servers and high-end client machines). Others might run on low-end platforms (e.g. mobile hand-held devices), with correspondingly weaker computational, graphical, and network resources. Allowing users and objects to move between such worlds requires a way to translate representations of objects, and the complexity of functions that are supported. This certainly involves strong game or VE design to understand how and whether tasks from one domain translate into the other, but also tools for supporting the automated translations between these varied settings.

Future Research Infrastructure Requirements

Research on scaling games and virtual worlds has strong requirements on infrastructure support. In general, it needs (1) support for workloads collection and generation (for instance, studying user behaviors to create models for creating synthetic workloads, defining metrics or benchmarks to evaluate scalability, etc.), (2) hardware infrastructure for conducting large-scale evaluations, and (3) basic software and tools for conducting experiments, collecting data and statistics, and analyzing results. For example, to evaluate scalability in terms of concurrent users, it needs a testing infrastructure that is able to drive workloads that emulate thousands of user connections as well as support the high bandwidth requirements in delivering the updated world view in real time to every user.

Broader Impacts

The hope for this research is that virtual worlds could one day become a pervasive “3D web” or “3D Internet” that provides real-time interactions, and that people could access information, learn, interact, and experience in virtual worlds in a way that they cannot do with the current 2D Web. Improving scalability could open the door to a tremendous number of new usages including events with thousands of people interacting, highly detailed simulations, richly interactive learning and training environments (for instance, training for large scale disaster rescuing, which cannot be done easily in real worlds), and usages that may not be even imaginable today. It could also revolutionize existing industries and result in huge productivity increases and cost savings. For instance, in fashion design, a $1.7 trillion industry, virtualizing the fashion design processes could result in 75% percent decrease in design time and 65% reduction in the cost of physical samples (Rattner 2009). In addition, by making 3D immersive environments well integrated with everyday computing activities, it becomes possible to develop engaging new applications for Science and Education that can reach the widest audience possible.

We might return to a lesson from history when considering federation and interoperability. The Internet succeeded with the advent of the networking "narrow waist" in the form of internetwork protocols (IP) and domain naming systems, which provided the common communication means between disparate sub-networks and different link-level protocols. The Web as an application layer above the IP succeeded -- beyond other technologies and experiences that were much richer and feature-complete at the time -- because it provided an easy way to share and display application-level information: HTTP was the "narrow waist" communication exchange, and HTML its common control/data platform. What is the corresponding narrow waist and common control/data representations for the large-scale virtual environments of tomorrow? Defining one that is sufficiently flexible (to support varied environments), powerful (to not limit functionality to the least common denominator), and extensible (to support decades of continued evolution, much as the Internet and web has), would have a tremendous impact in the way the Internet is used.

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2. Advanced Game Technologies

Dan Frost, Michael Mateas (Lead), R. Michael Young, Victor Zordan, and others

Introduction

Advanced game technologies (AGT) encompass the integrated scientific, engineering, and design research necessary to enable the advancement of existing forms and the creation of new forms of game-based expression and applications. Research in AGT is required in order to broaden what games can accomplish by providing new capabilities through hardware and software which afford the broadest possible range of interests and challenges. Beyond its utility for established game designers and producers, AGT will alter the landscape of game creation by making development of CGVWs available to non-experts, educators, non-profit organizations, and members of the public, as well as small, agile companies. As such, research in AGT is a necessity for unlocking the immense potential of game capabilities by migrating access from the elite to the masses, from an entertainment and commercial driven media form to the diverse and powerful mechanism to which many of the other chapters in this report clearly allude.

We posit that the current range of topics addressed by games developed to date is a small subset of those possible, especially as we allow a broad definition of games as

the space of *playable* computational representations. In our definition, we take as axiomatic that games (and related computational media) are *universal*, that is, anything one can express in other forms of media can be expressed in a game. Within this framework, current game technologies severely limit the types of computational representations possible, thereby limiting game forms and expression at large. Broadening games to include all playable computational representations, training and education, for example, reveals a large space of untapped potential. However, much of this new space is not supported by current game technologies and there is no directed funding initiative to explore this space. Deliberate stringent investigations to tap the potential of this space require AGT research which is specifically applied to the computational representations of directed areas of interest. For example, the design and construction of new game forms includes the representation of all game content within proper models which will need to be developed for new game areas. Further, hardware, architecture, user interaction structures and affordances, and means for engagement and inference are all required to support the development of specific new game forms.

AGT pulls from many sub-fields of computer science and other engineering disciplines, such as AI, graphics, databases, networking, architecture as well as vision, sensors, and cyber-physical structures. In addition, AGT draws from a broad and diverse list of disciplines outside of engineering such as psychology, perception, social science, media theory, and narratology. One might be tempted to make the argument that research support for game innovation is already handled as an application within many distributed funding areas. However, such a *decentralized* funding strategy does not support AGT and general games research in a valuable manner. Clearly, the most important topics in games research are not likely to be the most important to the distributed funding areas which each have their own unique and important foci. As such, each domain and its constituents will not to be concerned with determining what the topics of interest are to games, and will likely not agree on the importance to the extent of funding related topics at all, much less with a directed vision. As mentioned, among the features of AGT and general game research are many diverse disciplinary requirements, especially with respect to the goal of enabling new forms of game-based expression. Research in AGT is needed to support innovative advances into radically different approaches to development of CGVW applications.

In order to create new forms of games in directed content areas, AGT must be applied to develop new computational models in a diverse set of areas. For example, in order to enable complex social situations in games, an interactive story progression will likely be necessary which requires the computational modeling of insights from narratology and the dramatic arts. Creating compelling autonomous actors in those and other settings requires computational models derived from the study of physical interaction akin to human biomechanics coupled with direction and human-like cognition which may be taken from acting and psychology. As we narrow our lens further, more specific requirements emerge. For example, creating a game about Middle East conflict and its historical roots involves constructing a computational model about the related historically-grounded political conflicts. Similarly, using games to provide immersive environments where users can learn about foreign cultures and the culturally situated use of language is an important need that has recently been demonstrated to great success (Johnson and Valente 2009). This in turn requires a software architecture that integrates a simulated game world with social interaction and other components (see Figure 1).

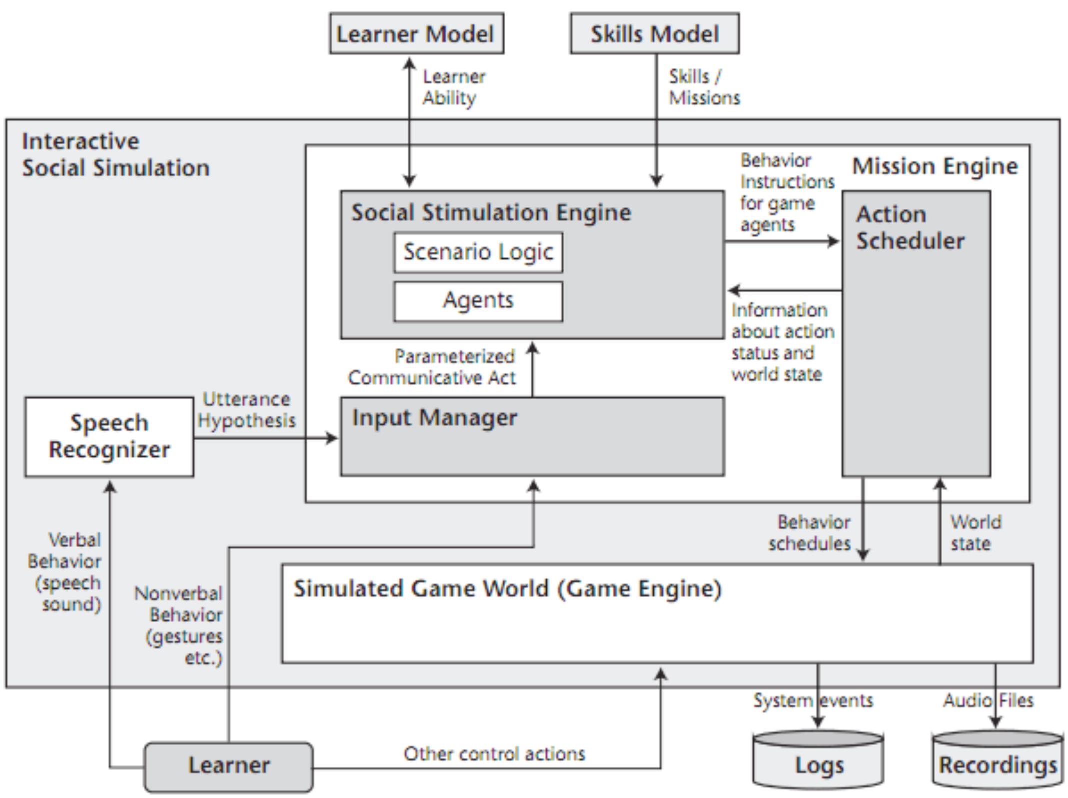

Figure 1. Architecture of an AGT for tactical language and culture training (Johnson and Valente 2009).

Advancing games research along the direction of desired thrusts requires fundamental discovery through AGT that includes new models that support such diverse content areas. Without a centralized funding mechanism which provides direction for these thrusts, critical exploration is easy to overlook. The result is a stunting of the growth and innovation in the impact and reach of games, especially in non-entertainment applications such as training, evaluation, learning, and so on where financial gain will require capital investment.

As a second important and largely parallel effort, fundamental AGT research in CGVW authoring support is necessary to enable broad creation of new game-based or virtual world experiences. Communicating through computational models requires a new kind of authoring in comparison to other forms. Fundamentally, game authors often construct software forms which encompass the parallel traces that may emerge through a player's interaction within the game. Desired expression is achieved in the union across each. Without accessible and flexible software authoring tools, authorship is limited. From many perspectives, games can be thought of as a new form of literacy that will require support from intelligent authoring tools, both for expert game designers as we move towards more radically adaptive and generative experiences in new content areas and for novices in order to open this new medium to broad participation and authorship. Similarly, games or game-inspired virtual worlds can serve as new media for original artworks, such that tools that facilitate the artwork creation process also merit further study and experimentation. The visual artist Sheldon Brown employs multiple generation, manipulation, and object reconfiguration tools running on high-performance computers to realize his interactive artwork, *The Scalable City* (Figure 2), that is then experienced within art galleries (Brown et al 2009).

Figure 2. Scene from an interactive fly-through of *The Scalable City* by Sheldon Brown.

Current topics: what makes AGT a cohesive area?

Play is the essence of games as a medium; that is, presenting the player with a series of challenges and opportunities for exploration that provide enhancing and/or desirable experiences. It is this property of deeply engaged interaction with an underlying simulation that makes games and other forms of interactive computational media powerful, expressive, and unique (Mateas 2001). In order to support rich, high-agency interaction for play, game technology must support computational models that are both learnable and actionable. To be learnable, a player must be able to make inferences about a game's state and build up a mental image or model of the underlying system as they interact with the rules of the game. This may not mean that they are able to completely reverse-engineer the system. Rather, a learnable computational model is one supporting the incremental development of simplified and partial mental models that successfully provide guidance for future exploration and interaction within the game rule system. This exploration is afforded through mechanisms of engagement, that is, a means for a player to affect the state of the game in a manner consistent with his or her desires. To meet this requirement, the game must also be actionable. Defining games as systems that employ such playable models distinguishes them from traditional systems and computational models in other disciplines such as physics or engineering, where cognitive properties of learnable and actionable are not factors.

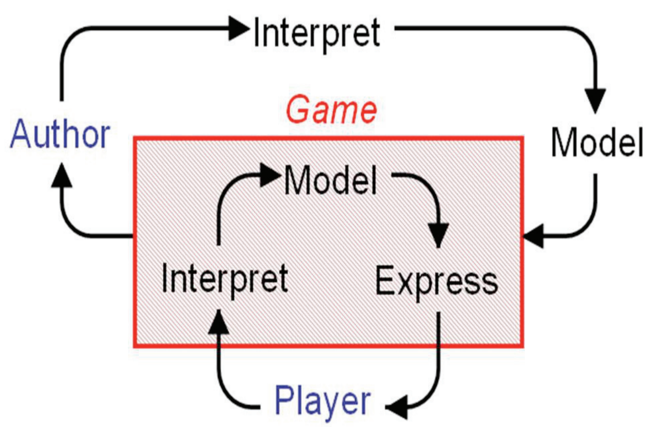

Figure 3: Crawford-like model of player interaction and authorship

Cohesiveness across games research is unified around the goals of enabling new playable forms and author expression of these forms. Adapting a model introduced by Crawford, we consider two interaction loops as depicted in Figure 3. The first loop is in an end user's interaction with a playable game model, namely how the player communicates with the game, how the game adapts to the input, and finally how the game conveys changes back to the player. A similar loop can be observed for game authorship, although the final expression of the authorship loop is the playable game itself. Incidentally, in games today, we are beginning to see further elaborations as players become involved in the authoring of the games they play, either through directly integrated end-user content creation or through the indirect modeling of player action by the game that leads to dynamic game adaptation (Scacchi 2011). Examples of game authoring through interactive play, game manipulation experiences, and social media for the associated player-developer community include recent commercially available efforts found in *Jumala.com* and *Roblox.com,* as displayed below in Figures 4 through 8, both of which seem to be targeting young game players as their core user demographic.

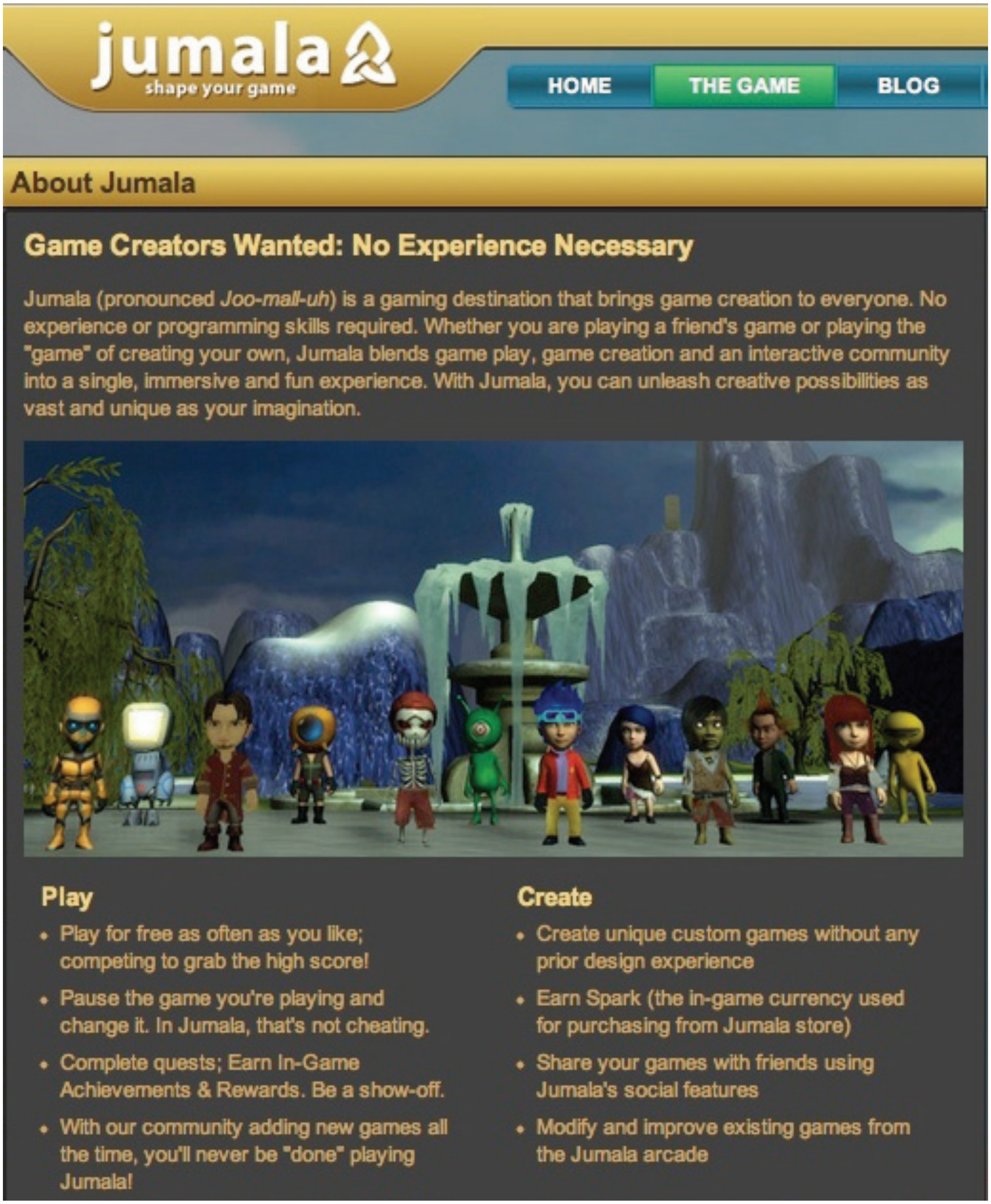

Figure 4. *Jumala*, an interactive game development and play world (source: http://www.jumala.com).

Figure 5. A reusable island object found in the *Jumala* object database, that can be interactively inserted into a game, and then specialized.

Figure 6. A tailored specialization of an island in *Jumala*, now shown with “winter” features, added objects, and terrain texture updates.

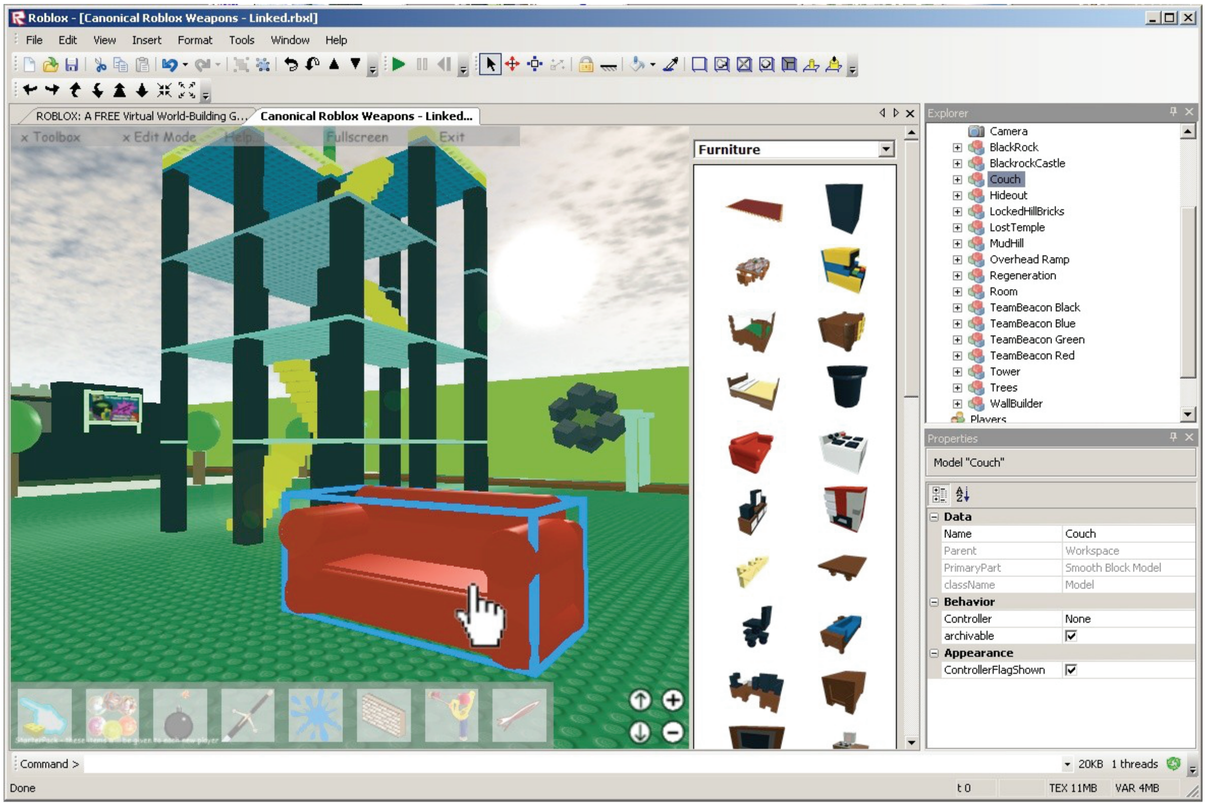

Figure 7. The interactive object and world editor for *Roblox.*

Figure 8. A character object browsing and tailoring database used in the *Roblox* portal.

Directed AGT research can support each leg of the described cycles of play and authorship. As such, the described model provides us with one organization for AGT research topics which can be structured around the augmentation, replacement, and/or exploration and evaluation of the various segments of these two cycles. Development of interpretation, modeling and expression directly relate to the notion of a playable model. Within the game loop, the model provides the dynamic rule system that underwrites the gameplay. Interpretation allows the player to take actions with respect to the model; as the model becomes more complex and generative, new and richer forms of player input (e.g. natural language and gesture) will be supported. Expression "renders" the internal state of the model (including potentially sound, music, language, as well as animation and graphics) in such a way that the player can understand the effects of her action on the model, and form new intentions with respect to the model. This similarly applies to the authoring loop. We highlight a list of topics from such analysis in the second half of this chapter.

Beyond identifying an organization of research topics, this model shows more clearly the need for AGT to be treated as a cohesive whole. From the cycles identified, we can see the tight interconnection between the various technologies. The impact of the whole is measured by the weakest link in the process. Taken separately, many technologies categorized as AGT fall into other categories of research, for example Artificial Intelligence (AI). However, it is critical that each of these technologies be grown and supported together. The advancement, understanding, and evaluation of each is critical to the next because the technologies inform each other regarding important characteristics, deficits, and so on. As such, they will invariably need to grow together in complexity and efficacy, since if one leg of the cycle is held back, the success of the entire system stalls. With such clear coupling between topics, housing AGT research interests in other domains leaves the forward progression of the entire domain at the rate of the weakest channels. Thus, while decentralized funding of games research is employed, there is no guarantee that research conducted in any related topic is truly helpful to overall progress in games.

Open research problems in AGT

Open research problems in AGT are found in the following areas: research infrastructure, game authoring design tools, automated game content generation, interactive narrative, and intelligent believable characters. Each is described in turn.

Research Infrastructure

Infrastructure requirements for advanced technology development range across a number of areas from software to hardware to data synthesis, access, and storage.

Open problems to be addressed by research in AGT touch all of these areas. As a means of required infrastructure for distributing advances, they may be deployed through standard, wide use tool-sets. For example, the construction of game-specific research prototypes would benefit from facilities such as readily accessible, extensible, general-use high-end game engines. Game engines provide access to libraries for graphics, networks, in-game physics and other software capabilities common to game creation. Commercial game engine providers typically license their tools at exorbitant sums and do not provide academic researchers access to their software. Without access to these engines, researchers must either create the engine infrastructure from scratch with each project or use tools that result in prototypes that are severely limited in quality or functionality. With standardized game engines, anyone can gain access to the latest AGT and game exploration and applications will benefit ubiquitously.

We point out another required infrastructure is in the metering or data recording of gameplay for study and comprehension. Millions of users play commercial games every single day. Currently, the data generated by their play, if collected by game makers, is highly restricted and access for researchers is rare. Currently, game companies do not include externally accessible metering or data collection tools in their products. Many of the research topics described in this document would benefit from tools for recording data that would be readily usable in commercial products as well as repositories of collected data ranging across all elements of game play.

Author design tools

Game designers currently lack software-based tools to facilitate the design process (Johnson and Valente 2008). While game engines and middleware libraries are useful for bootstrapping game implementation, and other software tools facilitate content creation for 3D models, textures, and animations, there is a lack of tools that explicitly support design. In professional game design, designers begin by working out interactions and basic game mechanics by building stripped-down, playable prototypes, either computationally or through other means. But gaining design insights from such prototypes, particularly insights regarding game rule interactions, is notoriously difficult. As games grow more complex and diverse, issues arise from these game design methods, forcing companies to employ legions of testers and debug programmers. In applications of games in new domains such as education, training, and public policy, there is an increased need for content experts, who themselves are not game developers and require specialized authoring tools to be successful at game design.

The fundamental challenge in building tools and techniques to support game design is that they must incorporate new models and metaphors. For design exploration via prototypes, this means enabling the creation of AGT for authorship that incorporate representations for both gameplay and in-game virtual world (or "level") design. This requires developing game design patterns and ontologies that are formal enough for novice game generation. Further, the game design process itself is still relatively poorly understood; while it certainly shares characteristics with software design processes, game design also has the characteristics of media design and art practice, making it a complex, hybrid process. Tools supporting user-generated content must provide expressive power while presenting the design space using constructs and metaphors that make sense to non-game-design experts. The design space must also be carefully constrained so as to guide the novice designer away from the many incoherent and unsatisfactory areas in the design space.

Automatic Content Generation

The current state of the art for game development involves the hand creation of much of the content in a game, such as hard-coded scripts, level designs, models, sounds, and animations. Current research efforts are tackling this problem in at least two different ways: game world/level object generation (Benes et al 2011, Brandao Silva and Coehlo 2011, Loiacono et al 2011, Smith et al 2011, Tutenel et al 2011), and semi-automated compositional scripting/generation of game levels from very-high level specifications (Chandra et al 2010, Pizzi et al 2010, Tate 2011). Procedural generation often focuses on producing digital terrains or urban landscapes that are otherwise devoid of characters or players. As hardware capabilities and consumer expectations increase, ever larger team-sizes are needed to produce the number and quality of assets required, resulting in ever more expensive production costs. This problem is compounded by the lifespan of game-based VWs. Unlike traditionally packaged game products, which are expected to provide one experience over a limited number of hours, virtual world games are expected to provide ongoing value to the users for extended periods of intensive gameplay. This requires that the game be constantly adjusted to account for human learning of game systems and their limitations.

Automatic generation of game content (procedural content) is a solution to this content crisis. However, computational content generation is difficult because expert understanding of the content to be generated is required and understanding of the designer’s intent, including desired player experience, must be encoded in a computational process. However, much of the procedural content generation tools, such as the GhostTown plugin for *Autodesk 3DS* (see Figure 9), simply create and texture geometric shapes, rather than objects/characters with rich semantic or animated behaviors.

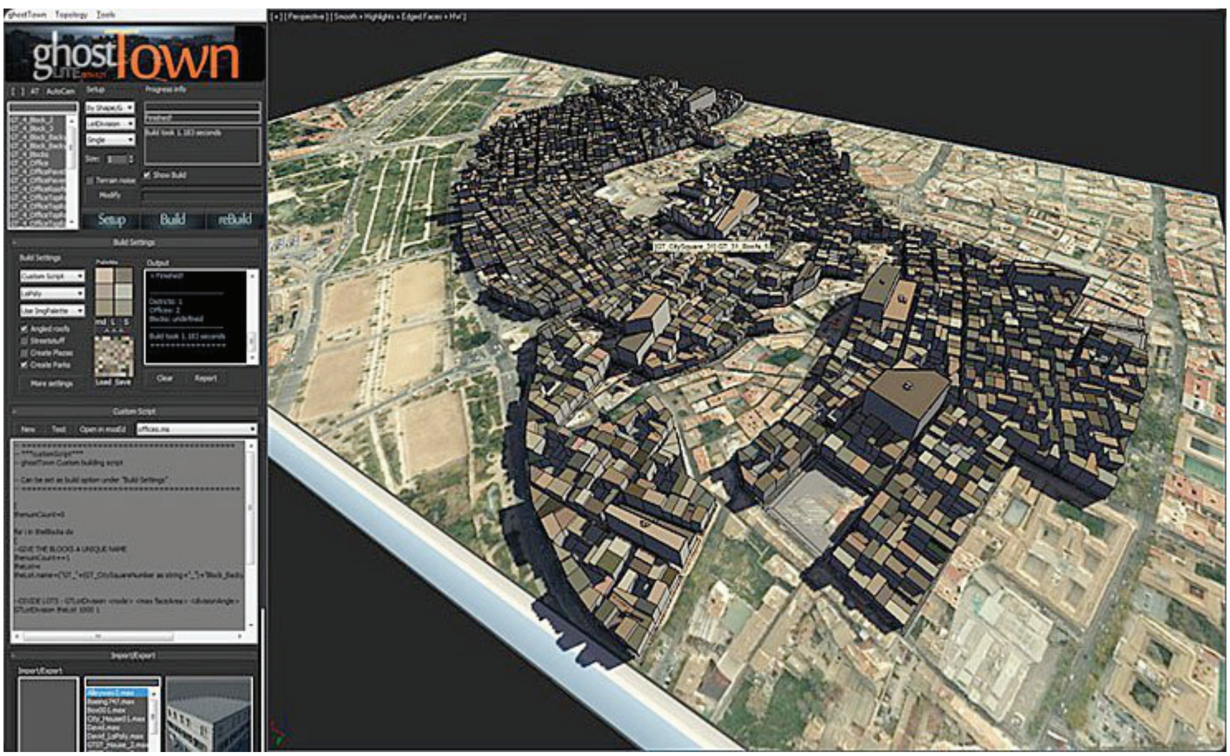

Figure 9. A screenshot of the GhostTown plugin for *Autodesk 3DS*, which is used to generate cityscapes.

Further, generated content must appropriately be integrated with the game (engine) architecture. In addition to addressing content needs, automatic content generation enables games whose content serves an underlying and evolving narrative model that dynamically adapts to specific play styles and goals of individual players. AGT has the potential to lower the barrier of entry for the creation high-quality games, broadening game creation and allowing it to serve niches and special interests that are not economically viable today.

Models of Interactive Narrative

By their nature, games have the potential to be an incredibly powerful storytelling medium. Aspects of story appear in game play both explicitly—as when players engage in an unfolding story as a central means of game progression—and implicitly, as when narrative techniques are used to design character behavior, cinematic cut-scenes, or background music that provide subtle cues to players about game dynamics. Narrative in games combines the cathartic pleasures (and reflection on the human condition) of well-formed stories with the exploratory power and high-agency experience of interaction (Harris and Young 2009). In fact, engaging story lines are central to several major game genres. Because narrative plays a role in our fundamental understanding of the worlds we experience (Barab et al 2011), a greater understanding of a generative model of narrative will empower games to engage in ways that go well beyond their current designs and applications (Riedl and Young 2011).

Fundamental research is required to enable the creation of rich, dynamic, compelling story lines tailored to individual players and that can be automatically customized to respond to unanticipated player actions. Typical approaches to the inclusion of story within games work by constructing, at design time, graph structures whose nodes represent fixed story points and whose edges represent pre-determined options or choices for player advancement along the plot. This approach does not scale: a choice graph has an exponential number of branches as a function of the number of actions that can be performed. This exponential explosion in required content is precisely why current generation games do not include sophisticated, non-linear plot structures. To address these limitations, future AGT research must build a foundational and computational understanding of character and story that can dynamically generate, sequence, and adapt story and character content. New models must be strongly generative, while supporting human designers in specifying, at the meta-level, the potential space of the story and characters.

Intelligent, believable game characters and VW agents

Many game settings require intelligent autonomous agents which serve to make the environment more interactive, immersive, and challenging. An in-game character can represent an autonomous agent can be defined as a subsystem that is capable of sensing the environment and manipulating itself or the environment in order to achieve specified goals (El-Nasr et al 2009). Complex agents maintain internal goals and a model of the environment that can change over time, in response to input. In some games the environment itself may have characteristics of an autonomous character. Autonomous agents in non-entertainment games can fulfill a wide variety of roles, such as teachers, guides, or evaluators. AGT research in such applications for education, training, assessment, and complex therapeutic interventions (such as for treatment of ailments like Autism Spectrum Disorder (Werry, et al 2001)), will rely on specialized and convincing autonomous agents.

Current and future research will develop autonomous agents with more sophisticated internal models. The *Tactical Iraqi* serious game, shown in Figure 10, helps train army soldiers in how to learn to speak and interact with autonomous, Iraqi-speaking in-game agents has demonstrated the tactical and life-saving value of believable avatars found in military-oriented immersive games (Johnson and Valente 2008, 2009).

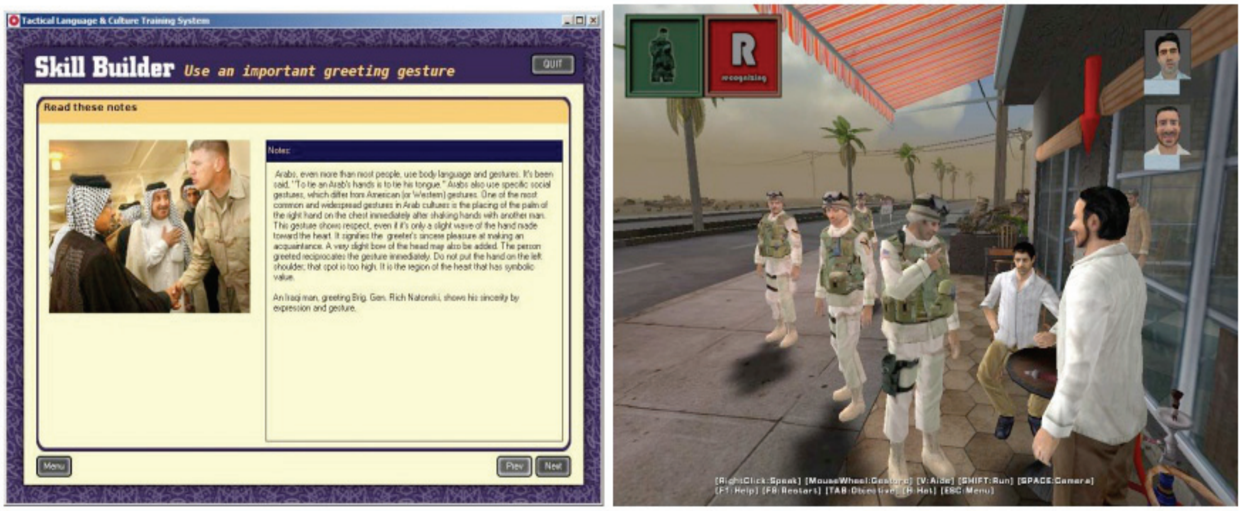

Figure 10. Screenshots from the *Tactical Iraqi* language and culture learning game employed by the U.S. Army for training soldiers through believable in-game avatars.

Although these will often be customized for individual domains and tasks, many aspects can be applied generally. Standard game character animation systems lack the ability to dynamically express believable action, both physically, which requires a deep understanding of biomechanics, and also emotionally, for example through mood-dependent behavior, facial expression, or evocative gestures. Consequently, in current state-of-the-art games, rich character interactions tend to be conveyed in non-interactive cut-scenes, in which the character's animations are hand-animated or hand-scripted. In order to support rich, non-player character presence, AGT needs to include better AI-driven internal cognition and personality expressed to an audience effectively, as well as more sophisticated, physics-driven bodies that know how to act given high level directives from their 'mind'. We envision AGT research that integrates rich mental processing for autonomous characters with compelling and expressive behavior action. Research is also required related to authoring support for creating custom autonomous agents.

Automatic Cinematography

Like conventional visual media such as film and television, access to the virtual world of a 3D game is provided through a camera moving within the game world's three dimensional space. In cinematic production, specification techniques like the use of storyboards use scene sketches to convey what the camera (and thus people who view the cinema) will see (cf. Pizzi et al 2010). Virtual cameras provide visual windows into the virtual environment, allowing users to perceive the game's space, interact directly with objects and characters in it and navigate between its areas. However, virtual cameras provide a powerful communicative capability that goes well beyond serving as a window into the virtual environment. The systematic control of a virtual camera, just like the control that a cinematographer exercises over a physical camera in a film, can be used to communicate meaning through situated game play within contextually rich game worlds, well beyond the communication of the world state explicitly appearing in the camera's view port.

For example, the choices made by a system regarding moment to moment camera control restrict or enable a player's access to actions in the game world. Restrictions on camera control restrict the knowledge that a player gains of the world and its dynamics. The way that a single camera shot is composed and the way that sequences of shots are put together rely on our pragmatic knowledge of filmic conventions to communicate implicitly about causal, temporal and intentional dynamics of the game world (Jhala and Young 2010). The limitations on current camera control systems mirror those of many elements of commercial game technologies. Current state of practice makes use of simplistic, one-off hand-crafted systems that provide limited dynamic capabilities and are often barely useful for game play. To address the potential of virtual cameras to complement the interaction between a user and a game world, AGT research must seek to increase our basic knowledge of the functions of the camera as a communicative medium and the dynamic, intentional generation of camera control in service of communicative game play goals. Because these approaches to camera control are grounded in game play, these models must all address on the production of real-time (e.g., greater than 30 frames per second) camera rendering.

Broader Impacts

Interactive, playable games include many serious applications in education and engineering as well as social, behavioral, and training inquiry. The impact of proper support and direction in games research will be directly measurable in many of these domains. However, its influence over other domains is not as clear but AGT will undoubtedly have tremendous impact in many ways. For example, better graphic cards and computer animation techniques have allowed for effective training simulations in medicine and emergency response.

In recent years, the convergence of social networking capability, modeling and simulation, and online CGVW and interfaces has led to the explosion of graphics-based personal computing. This has introduced three-dimensional, multiple-user VWs into mainstream activities. With the stabilizing infrastructure brought on by these changes, the time is ripe for growth in: (a) education for blended learning and distance education; (b) simulation environments for scientific experiments; (c) rapid prototyping of new products in industry; and (d) virtual training in corporate and military efforts.

Online CGVWs have become increasingly social, offering multi-player options such as integrating instant messaging applications through chat and voice, hosting game-related forums, and other collaboration affordances that enhance players' sense of community. Recent large-scale studies report on the pervasiveness in social applications of video games and social networking games in the culture at large. Gartner, Inc., analysts (2007) have identified emerging trends and warned IT leaders that they must take the initiative in addressing new markets and modalities of use and interaction based on their research conclusion that, "80% of internet users will be active in a virtual world by the end of 2011." The Pew Foundation reports, "fully 97% of teens ages 12-17 play computer, web, portable, or console games" and that their gaming experiences "include significant social interaction and civic engagement" (Lenhart, *et al.*, 2008). Further, they reported that civic gaming experiences were observed to be more equally distributed than high school learning opportunities in which primarily higher-income, higher-achieving, and white students participate more. However, current CGVW representations, designed for synthetic characters (i.e., web-based interactive agents), and compelling virtual worlds provided for humans players, are limited in how they enable CGVW development from the author and user perspectives.

Recent CGVW trends increasingly allow for user-generated content, This ability effectively strengthens users' sense of ownership and belonging in the environment. Similarly, social virtual environments have become *tabula rasa* worlds, the potential of which is actualized by users' imagination and growing knowledge of the interface. Advances in game-based research, particularly in AI and procedural content generation would provide game authoring capabilities to be shared with game players. This interactive loop would be strengthened by an intelligent world responding from in-world feedback.

Many game platforms have provided virtual world construction tool-kits for developing open cyber environments that are now used by several institutions as distance education solutions, blended learning options and research instruments.

Represented by avatars, users engage in mediated social interaction including a full range of social interaction and contact (Schroeder, 2002). Researchers have demonstrated that computer-mediated communication (CMC) and multi-user virtual environments (MUVE) are capable of projecting social presence (Chou, 2001) and could provide an online environment that surpasses other forms of CMC with respect to social presence and interactive communication (McKerlich and Anderson, 2007) Indeed, Rheingold (1991) defines virtual reality as an experience in which a person is "surrounded by a three-dimensional computer-generated representation, and is able to move around in the virtual world and see it from different angles, to reach into it, grab it, and reshape it" (p. 17). More recently, Johnson and Levine (2008) describe virtual worlds as "inherently immersive" (p. 161) arguing that virtual worlds are "richly expressive environments that immerse the participant in a setting that includes sound and visual cues, rich textures, and realistic perspective...and vividly create a sense of place" (p. 161).

CGVW offer more presence affordances than other forms of CMC in that they are designed to foster social interaction and the formation of groups and communities (Johnson & Levine, 2008). They have the potential to "significantly reduce the subjective feelings of psychological and social distance often experience by distance education participants" (McKerlich and Anderson, 2007, p. 35). Bringing courses in CGVW would allow for a rich and compelling learning environment while maximizing distance learning benefits, such as reaching nontraditional students, students with disabilities, and promoting international collaborations.

The 'distance' in distance education implies that physical and geographical separation is correlated with psychological and social distance. It is therefore tempting to assume that students feel disconnected and isolated from the instructor as the physical distance grows between them as well as the students feeling disconnected from their peers. However, the nature of the technology used in delivering instruction exhibits its own distance rate. For example, students rate independent study on campus (e.g.,via personal tutorials) lower on distance, compared to self-directed independent reading (textbook). It may be more useful to consider distance education as pedagogical distance. Moore (1993) argues that pedagogical, or 'transactional distance' (TD) is a function of two sets of variables, structure and dialogue ('constructive interaction'). Hence, the manner in which a program is designed and conducted can result in higher or lower levels of dialog between the learner and the instructor. Saba and Twitchell (1988) consider telecommunication-based technology an essential core to distance education and elaborates on TD, using a system modeling approach. Saba (2007, p. 51) defines TD as "an open system residing in a larger environment in the instructional systems level which is in turn part of a larger system in the hierarchical model."

Research suggests that social presence impacts online interaction (Tu & McIsaac, 2002), user satisfaction (Gunawardena & Zittle, 1997), depth of online discussions (Polhemus, Shih, & Swan, 2001), online language learning (Leh, 2001), critical thinking (Tu & Corry, 2002), Chinese students' online learning interaction (Tu, 2001), and more. Universities have used web based learning management systems such as BlackBoard® to develop their online courses, facilitating instructors' reuse of class materials and augmenting the global reach of educational activities. Virtual worlds are likely to figure heavily in next generation of online systems employed by educational institutions that seek to integrate more options for human interaction. Imagine an environment where an educator can send his students to learn and review content: As the student avatar moves and interacts with the world, the world intelligently reacts and changes, adapting to the evolving knowledge creation and acquisition of the student. Imagine a virtual world that evolves according to the individual learning needs and styles. Content and assessment are integrated objects within that environment. Imagine a virtual world kit that allows educators to create such environment without programming and scripting knowledge. The students can be mobile and global. The same applies for corporate functions, including team collaboration, prototyping, and recruiting.

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3. Media, Art, Culture, and History (MACH)

Peter Krapp, Elizabeth Losh, Robert Nideffer, Noah Wardrip-Fruin (Lead), and others

Introduction

Computer games are fundamentally technology *and* media. Basic research questions bridge these two domains, just as the fundamental bioinformatics research questions bridge technology and biology.

If we can meet these research challenges, we can chart a successful future course for games, one in which they are created and played by a wider diversity of people, contribute meaningfully to our education and self-understanding, and can accelerate the pace of innovation that has been the industry's driver.

But a significant challenge presents itself. Not only are the research questions involved themselves complex and deep problems (Bogost, Mateas, *et al*. 2005, Harrigan and Wardrip-Fruin 2004, 2007, 2009), but our research models themselves – from disciplinary structures to funding institutions – resist collaboration between technology research (e.g. computer science, electrical engineering) and media research (e.g. humanities, arts).

Addressing such structural issues is beyond the scope of our work here. Instead, in the next section we offer selected examples of areas in which hybrid practitioners and teams are making important progress, simultaneously pursuing STEM and MACH approaches. From there we continue to an identification of three major areas of future work: practice-based interdisciplinary research, new forms of evaluation, and archive-oriented research.

Current Findings

In the last decade, Game Studies has become a recognized scholarly field in which researchers in media, art, culture, and history are making significant contributions.

Regular international conferences addressing Game Studies include DIGRA (Digital Games Research Association), FDG (Foundations of Digital Games), DAC (Digital Arts and Culture), the ACM conference CGIE (CyberGames and Interactive Entertainment), Game Developers Conference (GDC), SIGGRAPH (ACM's Special Interest Group on Computer Graphics and Interactive Technologies), AoIR (Association of Internet Researchers), DML (Digital Media and Learning), and PCA (Popular Culture Association). There are also speciality conferences such as State of Play and Philosophy of Computer Games that emphasize connections between traditional humanities fields, such as law and philosophy, and emerging interactive technologies.

There are a number of peer-reviewed journals devoted specifically to games research, which include *Games and Culture*, *Game Studies*, and the *Journal for Virtual Worlds Research*. Book series from academic publishers that include MIT Press, Minnesota, Princeton, and Routledge also recognize the importance of this emerging field. Universities are also creating institutes such as the CMU Entertainment Technology Center (http://www.etc.cmu.edu), Game Design Initiative at Cornell University (http://gdiac.cis.cornell.edu/), NCSU Liquid Narrative Group at NCSU (http://liquidnarrative.csc.ncsu.edu), NYU Game Center and Social Game Lab (http://gamecenter.nyu.edu), Singapore-MIT Gambit Game Lab (http://gambit.mit.edu), UCI Center for Computer Games and Virtual Worlds (http://cgvw.ics.uci.edu), UCSC Center for Games and Playable Media (http://games.soe.ucsc.edu), USC Institute for Creative Technology (http://ict.usc.edu/), and UWashington Center for Game Science (http://www.centerforgamescience.org), as new U.S. based research centers that are focusing on CGVW technologies, studies, and practices.

Results from university-based research are often disseminated rapidly through academic blogging channels, thanks to popular blogs about gaming with teams of faculty writers that include *Terra Nova* and *Grand Text Auto*.

This matrix of associations, conferences, journals, publication venues, and academic centers has fostered the rapid growth of an international research community that has identified a number of critical research questions that are directly relevant to the NSF mission. Thus far the most important prior work on these research questions has emerged from three directions.

The first direction is practice-based research. Here the approaches of media arts, technology research, and independent game production come together to produce novel game experiences infused with university research approaches. We describe below how this remains one of the most important areas of future research problems. Here we wish to note the importance of the prior results from this sort of work. Projects such as *Facade* (Mateas and Stern, 2005) and *DinoQuest Online* (Scacchi, Nideffer, and Adams, 2007) create university partnerships with the game industry and non-profit informal education enterprises (e.g., Art galleries, museums, regional science centers). By bringing full game experiences to completion they identify and answer research questions that a system aimed only at paper publication could avoid. They are experienced by hundreds of thousands of members of the public, demonstrating a novel path to research dissemination. And they are also the only proven approach to industry dissemination for university research results in games, given that most game companies lack the formal research groups common in other technology-based industries.

The second major direction is the emergence of what might be called “hybrid humanities.” While a significant amount of work in game studies is similar in its approach to areas such as film studies and literary analysis, a new set of practices is bringing humanistic insights and methods to bear on the specifics of media technologies. This requires humanists with training in STEM approaches and domains, and produces new understandings that are founded on the deep media expertise of the humanities. This can help explain the most important factors in successful new approaches, identify the causes of recurring difficulties, or even find previously-unidentified potential in historical approaches. Three prominent hybrid humanities groups are identified with the terms *software studies, digital humanities,* and *media archeology* — each with a somewhat different scope, focus area, and intellectual history, which are beyond our scope here (Fuller 2008, Svensson 2010, Hertz 2009).

Finally, the third major direction is that of information scientists and digital archivists working with “big data.” This takes the archival expertise of the humanities and combines it with new technical approaches in data mining, knowledge discovery, and so on. Already the research results in this area have identified an important new set of questions and approaches, such as those arising out of the multi-institution *Preserving Virtual Worlds* project (McDonough, Olendorf, *et al.*, 2010). This direction is discussed in more detail below, in the context of describing important MACH research problems and infrastructure.

Research Problems

Three major areas present themselves for future work. Each configures the relationship between STEM and MACH disciplines differently, but all share the need to bring the full creative power of the arts and the full interpretive power of the humanities to bear on the construction of novel technical systems that have the potential to move the field of computer games and virtual worlds forward dramatically.

Practice-Based Research

In the arts and design, much research proceeds, and many research questions are identified, through the practice of creating media that is intended to reach audiences (cf. LaFarge and Nideffer 2002). As discussed above in Current Findings, integration with such practices has been an important feature of some of the most influential research done in the CGVW field thus far. (We will also discuss some aspects of how such practices are important for evaluation below.) We identify four primary areas in which such research models are essential for moving forward.

Problem of Meta-Authoring for Current Game Assets

As has been noted repeatedly since the introduction of current-generation consoles, the game industry is on an unsustainable upward trajectory of game asset creation. In order to create games with a greater sense of vastness and responsiveness, game companies laboriously hand-create huge numbers of variations on everything from three-dimensional models to lines of character dialogue.

As discussed in this report's chapter on Advanced CGVW Technologies, defining methods for procedurally generating such game assets is a major technological challenge. But we cannot approach this as a *purely* technological challenge. Such approaches have no chance of working unless they embody approaches appropriate to a wide variety of artistic creation and, critically, provide authors with powerful new game authoring and meta-authoring tools, such as through a new generation of game software development kits (SDKs) as shown in Figure 1, procedurally generated and transformed virtual worlds, as seen in Figure 2, through CGVW *modding* techniques (Cleveland 2001, Kelland 2011, Scacchi 2010, Steinkuehler and Johnson 2009), or through *machinima* (Lowood and Nitsche 2011, also http://www.machinima.com/). While some work can be pursued on such controls in the abstract, it is only in the process of creating a specific work of media—that is, in the context of practice-based research—that the full training of arts and design practitioners will be able to productively shape technical approaches of current research and bring to light next-generation research questions (Daniels and Schmidt 2008, Flanagan 2009).

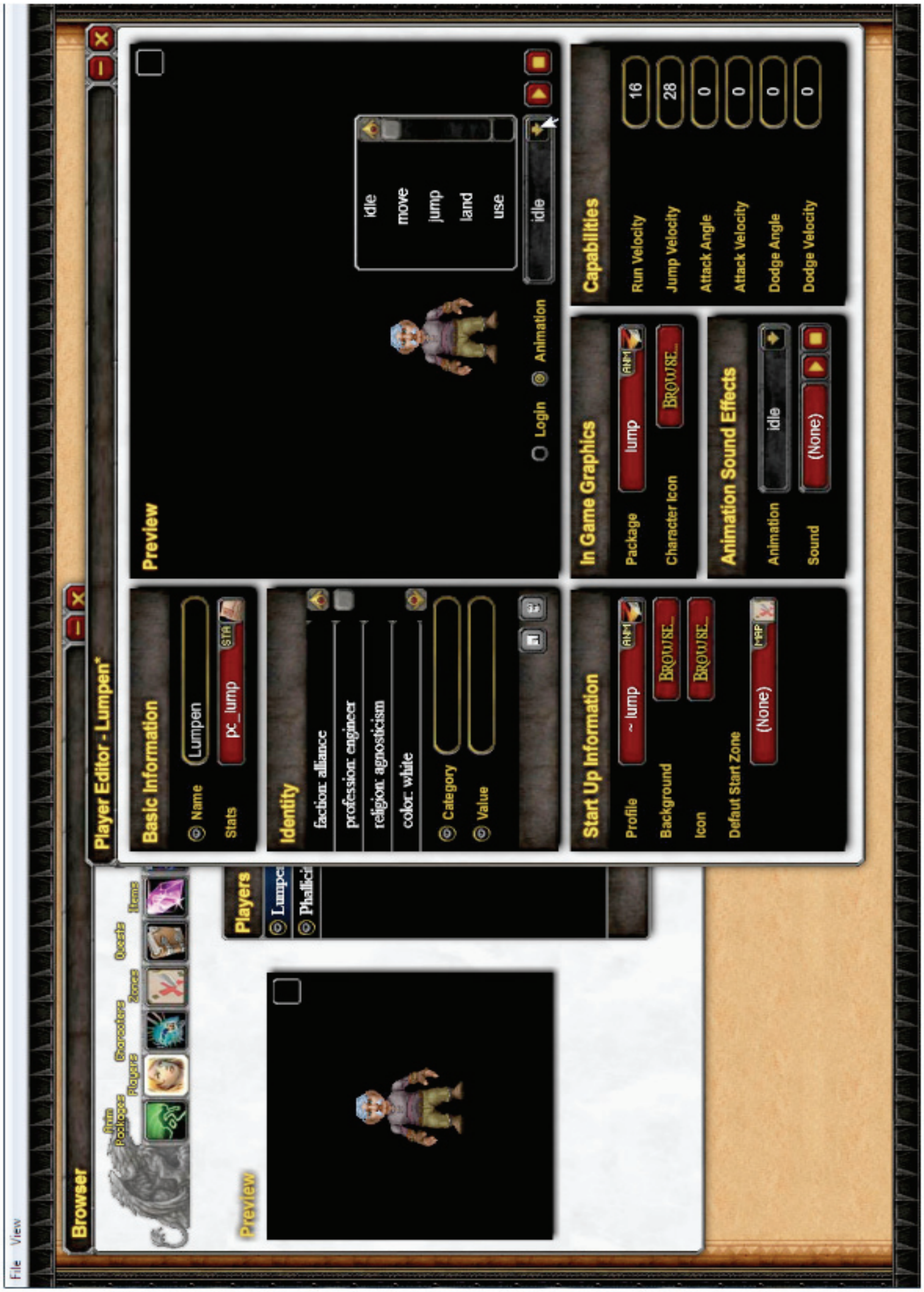

Figure 1. Screenshot from the *WTF?!* Software Development Kit for authoring and meta-authoring game assets (Nideffer 2010).

Figure 2. A view of T*he Scalable City* by Sheldon Brown, created as a virtual world that generates, composes, and reconfigures variations of familiar objects in a synthetic suburban terrain (Brown 2011, Marsh 2011).

Problem of New Expressive Spaces

The current expressive spaces of games are, as noted above, those that can be reached by brute force authoring efforts. Procedurally generating such content will make such games more tractable to produce and open up certain areas that currently cannot be approached because of the combinatorial explosion of game assets that must be created. However, even this is a limited horizon. We must also bring fundamentally new expressive models to games (Mateas 2001, Wardrip-Fruin 2009). While the current practices of CGVW excel at the representation of physical space (and, to a lesser extent, at the representation of resource allocation and transformation) they are quite weak at other sorts of representation.

Figure 3. A screenshot of the game, *WTF?!* which serves as a parody of *World of Warcraft* while reflecting on latent cultural values and assumptions built into games, through expressive in-game characters representing Sigmund Freud, Karl Marx, and Mary Daly (Nideffer 2008).

This has perhaps been most commonly discussed in the context of narrative—most games that employ narrative alternate between narrative progression and game play, because the narrative is not represented in the game's playable systems. A fundamental set of research questions for the future of CGVWs focuses on expanding the expressive space of playable game systems, especially in areas such as narrative, character, rhetorical structure, and belief systems. For example, CGVWs may serve to identify and transform the unquestioned master narratives of resource accumulation and social dominance role-playing games to embrace alternative critiques of social action and actors, in the *WTF?!* game, here showing in Figure 3, in-game character of Sigmund Freud (on left) who poses quests and offers information on playing with one's self-identity and appearance (Nideffer 2008). Expanding the expressive space will enable both more compelling games and more powerful CGVW applications in domains such as education, cross-cultural communication, and wellness (Barab et al 2011, Wardrip-Fruin 2009). But progress in these areas will require a combination of insights from technical disciplines and the humanities and arts—where expertise in areas such as narrative and rhetoric is concentrated. Further, it is only through the creation of full games (practice-based research) that the effectiveness of new combinations of algorithmic and representational elements can be explored and evaluated.

Problem of Authoring Inclusiveness

Especially as we work to expand the expressive spaces of games, we must work to expand the groups that can author them. Currently, game authoring is restricted to a much smaller group than authoring through text—and even significantly more restricted than authoring through video. It is only when game authoring can be accomplished by wide and diverse groups (including teachers, journalists, emergency rescue experts, and even children) that their power as a medium of communication and persuasion will be realized. Some prominent projects such as Microsoft's *Kodu* and the MacArthur Foundation-funded *Gamestar Mechanic* are attempting to broaden authoring for the games of today. Recent commerical efforts by Jumala.com (http://jumala.com/social) and Roblox.com (http://www.roblox.com) offer some alternatives, but do so by limiting the visual language of game design to conventional styles that all subsequent games tend to readily reflect and embody. But research has only begun on how to broaden authoring for future games, with much more powerful expressive capabilities, as suggested in the earlier chapter on Advanced Game Technologies in this report. Currently, the vast majority games can only be hand-crafted, often by those with significant experience in both computer science and MACH fields. Identifying and evaluating methods for opening the creation of such games to a broader public is another area in which major research questions present themselves.

Problem of Data Capture

Data capture is an important element of games. Motion capture of professional performers is used in authoring game animations. A different kind of motion capture allows for new kinds of game play through gesture for those using Nintendo's Wii, Sony's Move, and Microsoft's Kinect controllers. GPS motion capture enables certain kinds of location-based gaming. But all focus on the capture of movement, just as most of today's game technologies focus on the representation and simulation of physical space. As games move toward deeper representation of other important elements of life (such as narrative and belief systems) both authoring and play will require the capture of a significantly expanded set of data. Meeting this challenge will require investigating major new research directions in known areas such as natural language understanding and story interpretation, as well as pioneering new areas, such as those that might capture and interpret movements in social and economic status. While some progress in these areas might be made through traditional research approaches, it is through the specifics of creating particular games (e.g., a game presenting a particular vision of history through its systems, drawing on data captured from a large archive of historical material) that the intertwined MACH and STEM questions will be fully understood.

In addition to the four research areas identified above, practice-based approaches are also essential for the future of game research for another reason: the creation of full, playable games is the most proven method through which game-specific research is disseminated into industry, both technologically and conceptually.

New Approaches to Evaluation

The evaluation of game research, both while it is ongoing and after it is completed, is complicated by the dual nature of games as technology and media. While some infrastructure research for games may be possible to evaluate purely in terms of measures such as efficiency, this will not help identify the strengths and weaknesses of research in areas such as expanding the expressive space of games.

One field that makes important contributions to evaluating game research, and which will no doubt continue to do so in the future, is human-computer interaction (HCI). However, it is important to note that most HCI research is oriented toward tools, rather than media. Further, while HCI techniques can be quite effective at reducing the difficulties and unexpected outcomes that users experience with technology, for games it is precisely certain types of difficulty and unexpectedness that make them compelling experiences. Given this situation, it is important to look beyond traditional HCI studies (e.g., Erickson and MacDonald 2007), towards ways that HCI and CGVW research can be combined with approaches from the arts, design, and humanities. The goal here is to constructively engage games' central media and play structures (Bogost 2011). In particular, we identify four areas in which further research on new MACH-connected evaluation approaches could be particularly fruitful:

Iterative Prototyping and Playtesting Methods

Design communities, and particularly game design communities, have developed methods of iteratively prototyping and playtesting CGVW systems. Early prototypes often start with many (or all) elements of the game represented through physical materials, rather than computationally. These prototyping and playtesting methods are remarkably effective at guiding work on game development, and in some cases draw heavily on established HCI methodologies, but little work has been done to understand how they can be employed in evaluating and guiding game technology research. Answering this question, and producing findings that can be used to guide both researchers and funding agencies, is an important goal. Hertz's game-inspired artworks like *OutRun* (shown in Figure 4) and *DOOM Reflection Wall* (Hertz 2011) demonstrate how physically embodied and playtesting in contemporary art exhibitions create original interactive experiences that are playful and challenging, yet reflective and evaluative.

Close Reading and Interpretation Methods

Game research aims at significant advances in an area that combines technology and media. Given this, we cannot solely use methods developed for evaluating and understanding technology—we must also investigate those used in media disciplines. One of the most promising directions is building on the humanities tradition of "close reading," but turning this technique not only to the surface appearance of games but also to the system-level operations of games. This type of analysis has been pioneered by researchers such as Phil Agre (outside media-connected areas of CS) and is now developing in the software studies community (Fuller 2008). Understanding how close reading—and other interpretation techniques developed in the evaluation and understanding of literature, film, and other forms of media—can be most fruitfully adapted for evaluation of CGVW research is an open research question. In addition, social media and databases may serve and be closely read as game play records that may reveal player's expressive experiences in response to situated game play, as demonstrated by Nideffer in the pervasive game, *Unexceptional.net*, as suggested in Figure 5, and the Twitter and live news stream data feeds in the game prototype, *SPEW* (Nideffer 2011), seen in Figure 6. Blogs, databases, news feeds, and tweets provide new ways and means for critically reading (and writing) through new CGVW play experiences.

Figure 4. Artist Brody Condon test driving the now drivable *OutRun* video game arcade machine that has been grafted onto an electrical vehicle while maintaining and reimplementing the legacy 2D *OutRun* arcade game as user interface and vehicle “windshield” for play-driving the vehicle (Hertz 2011).

Peer Review Methods from the Arts

Game research seeks major advances—not incremental ones. In the arts, major advances in media are not evaluated through measures such as focus groups or box office receipts. Rather, the arts use methods of peer review, both through jurying work sent in response to open solicitations and through the work of curators who are employed to select work through processes involving site visits, interviews, and other means of investigation. At the moment these methods are rarely used to evaluate game research, and there is little understanding of whether and how such evaluations are seen as significant in the game research community. This is unfortunate, because it provides no incentive for game research projects to produce completed games - not only making this sort of evaluation impossible, but also greatly diminishing the chances of dissemination to industry, broader impact with the general public, and discovery of research questions that arise when building fully grounded audience experiences. Understanding how best to employ arts methods of peer review in game research is an open research question.

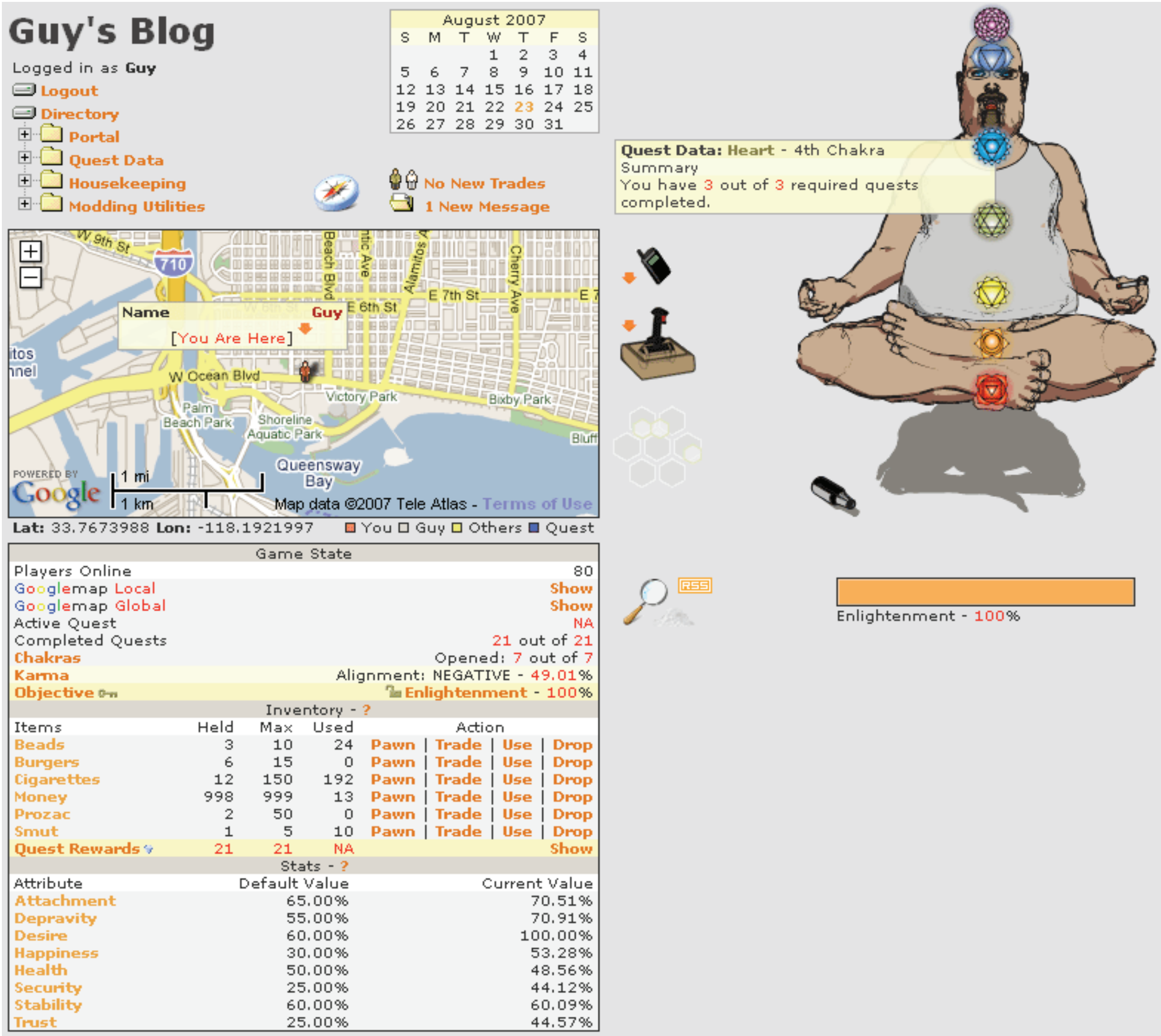

Figure 5. A demonstration of how blogs and other social media can be integrated into a game to capture and provide live data records of progress and "player state" stored within persistent databases that can be externally accessed and studied (Nideffer and Wang 2009).

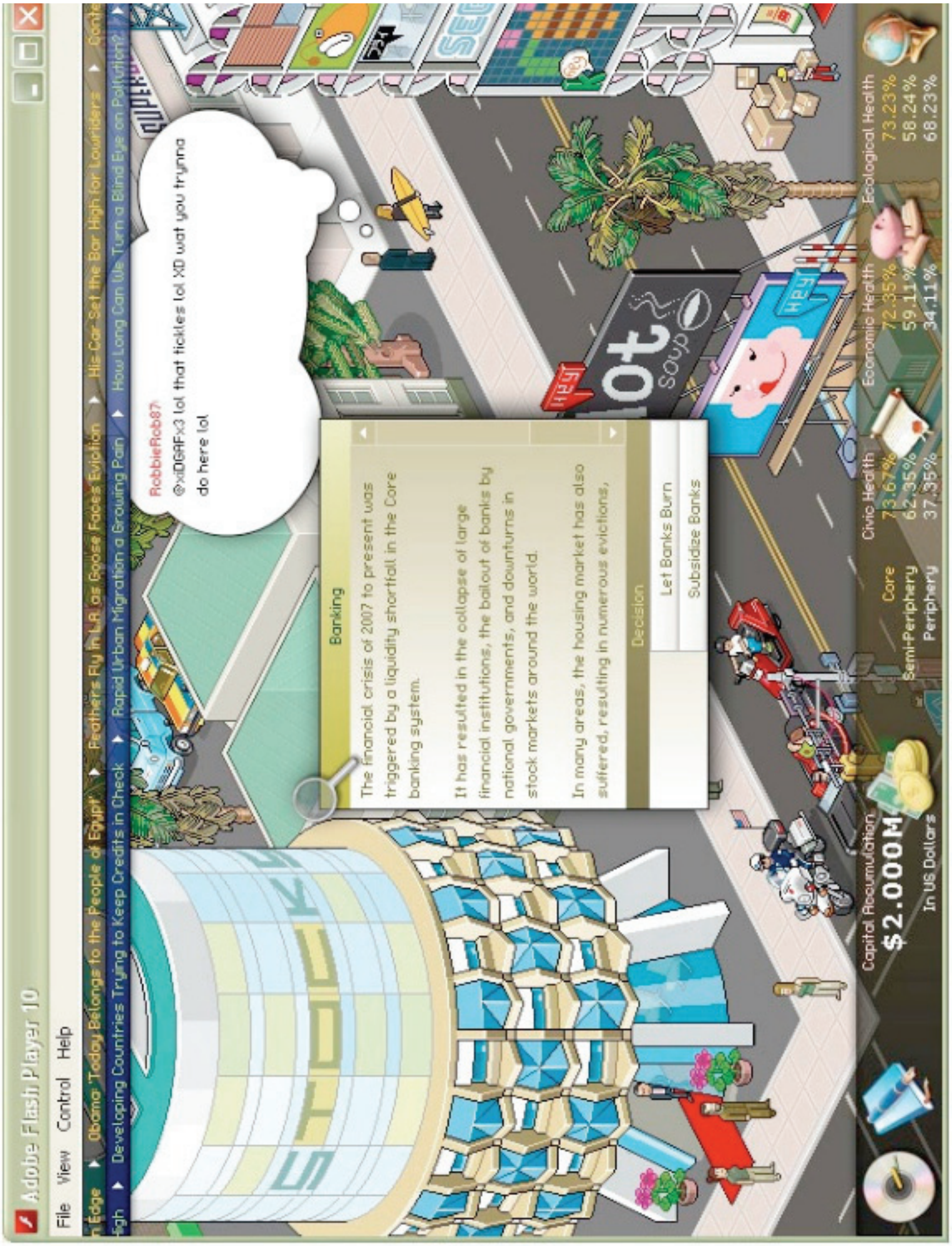

Figure 6. A view of *SPEW* that demonstrates the incorporation and usage of Twitter (upper right) and streaming news feeds (top screen banners) to drive CGVW play or navigation experience (Nideffer 2011).

Archive-Oriented Research

How can disciplines studying and making next generation games and virtual worlds have access to their own history as an interactive literature to draw upon (Cohen and Rosenweig 2005)? This is one the most pressing research problem in the intersection of MACH and CGVW disciplines. Access to materials from archived games is needed for both experimentation and interpretation in a field that is rapidly expanding to include games for mobile devices and ubiquitous computing technologies, which pose unique data capture and infrastructure challenges. CGVW-based animations, video records, and documentary game play in the form of machinima (Krapp 2011, Lowood and Nitsche 2011) are essential elements that capture, represent, or re-represent what and how CGVW play experiences can be embodied for future study and recollection. Industry reports indicate that there are now billions of online views of machinima video (see http://www.machinima.com/). Subsequently, it seems clear that such CGVW-based cinema are amenable to “big data” research methods and studies, since they already fill vast digital libraries and online storage repositories like *YouTube*. Furthermore archivists disagree about basic strategies for preserving the products of so-called “dead media” (http://en.wikipedia.org/wiki/Dead_Media_Project)that were once playable on defunct platforms: some favor “emulation” while others favor “migration.” Next, there are difficult technical and legal challenges to making games citable, annotatable, and replayable and to capture code, individual gameplay, and digital models and maps that may be user-generated (McDonough, Olendorf, *et al*. 2010). Finally, it may also be appropriate to consider (and encourage) how a new generation of CGVWs could be designed and developed to support historical studies, whether focusing on historical events, social trajectories, or people (Wang 2010). CGVWs can weave together historical facts and online artifacts (music (Peppler et al 2011), poetry, songs, images, videos, speeches, etc.) together with narrative storylines from regional or national cultures.

Future Research Infrastructure

We believe that future research advanced in CGVWs through MACH studies will depend on globally accessible archives (repositories) that represent findings about computer games, as well as preserves and stores the games themselves for future generations. This is similar in spirit to the global data repositories envisioned for uses in other scientific research domains where multidisciplinary studies are evermore common, such as found in the world of free/open source software development studies (Gasser and Scacchi 2008). The repositories needed require computing resources to address the resulting demands on networks, storage, support for multiple data and video (machinima) formats, DRM issues, data corruption, and sustainable portals for access. This project would extend the archival work already done by groups like the *Center for History and New Media* (http://chnm.gmu.edu/) and the *Preserving Virtual Worlds Project* (McDonough, Olendorf, *et al.*, 2010, http://pvw.illinois.edu/) and consider information design strategies in the context of how games will be cited, annotated, and replayed in ways that can capitalize on work to be done by the *Open Beta* project with Media Commons, and by the NSF-funded *Cultural Analytics Project* at UC San Diego.

Broader Impacts

Games have historically been a driver for technical innovation by serving as a way to demonstrate the efficacy and adaptability of new technologies to the public. Innovative technologies also have been repurposed subsequently by the game industry for use by consumer audiences. However, the game industry has few incentives to create next-generation technologies that are comparable to the technologies that corporations have repurposed in the past, given their relatively narrow research and development agendas and short-term mass market-driven goals. Federal-level sponsorship of games-specific research is needed for related STEM-based research and MACH practices to continue to thrive, and game play and development can serve as a gateway to STEM education (Lowood, Bainbridge, *et al.* 2010).

CGVWs can do more and say more in our culture. CGVWs can address more publics and diversify cultural production beyond the science fiction and fantasy fans who were once the core audience. CGVWs can also create more connections between informal learning and formal education and can ameliorate the participation gap that has supplanted the digital divide (Jenkins, 2006). They can serve as a mechanism for collective problem solving, whether solving puzzles about protein-folding in *Foldit* (Cooper, Khatib, et al. 2010), or imagining social responses to oil shortages and other resource crises in games created by the Institute for the Future and game designer Jane McGonigal (2011). Games can foster more cultural inclusion, engagement, and experimentation as user-generated content, procedurally generated content, and real-time rendering improve, but without cultural investment that develops the critical capacities of players and designers, the richness of the resulting products will be stunted.

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4. Anthropological, Behavioral, and Sociological Studies of CGVW

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Introduction

More than ever before, computer games and virtual worlds are part of the everyday experiences of children and adults in contemporary society, spanning age, gender, social class, cultures and subcultures. Scholars dedicated to the study of CGVWs across the social sciences recognize the importance of understanding how players co-construct experiences in computer games and virtual worlds, in concert with the technologies and physical-world cultures that shape these experiences (Corliss 2011, Lindtner and Dourish 2011, Malaby 2007). At the same time, the power of code to shape experience must also be examined and theorized. The proliferation of paratexts (online artifacts) such as forums and blogs related to CGVWs, and derivative productions such as machinima and fan art, are important resources in understanding the reach and significance of CGVWs.

To address anthropological, behavioral, and sociological questions of CGWs, scholars employ a range of methodological approaches. Of central concern are better ways to understand how meaning is made in games and in virtual worlds, as well as how culture and society play important roles in shaping online experience. A challenge facing researchers who seek NSF funding is the bias towards quantitative methodologies. Many calls for research specify what method(s) to use, rather than focusing on research problems to investigate. Yet many research questions cannot be answered using quantitative methods, in particular those questions that address context and meaning. In the Research Problems section, we provide examples of such questions.

There is a pressing need to build forms of social infrastructure in support of CGVW research. In particular, workshops for CGVW researchers and funding that allows for the synchronization of research projects would facilitate the formulation of new research questions, helping researchers share resources around similar topic areas.

Current Findings

Two decades of research in the social sciences and humanities has produced a complex account of how individuals make sense of and co-construct their experiences within and around CGVWs. In that time we have moved beyond simplistic effects models and beliefs that we experience life online in ways divorced from ideologies related to bodies, race, gender and other identity factors. Researchers working in disciplines including anthropology, sociology, communication, economics, political science, rhetoric, law, and related fields have worked to adapt and innovate methods and theories to account for participant activities and beliefs in CGVWs. The role of the technologies themselves as actors producing experience is a central concern. While we cannot recount all major findings here, the following represents some of the most relevant and important pieces to emerge from our collective experiences.

Researchers have found that users of CGVWs are active, engaged meaning makers who have developed social practices that go beyond original designers' intents. These practices may be anticipated and incorporated by developers into iterations and updates of CGVWs (Paul, 2009b; Taylor, 2006). For example, participants create software products, mods, machinima, and other artifacts that are designed to augment, critique, and supplement original creations (Lowood, 2007; Sihvonen, 2009; Pearce, 2009; Scacchi 2010, Sotamaa 2010). Thus the people who play with CGVWs are vital components of any study of how technologies of CGVWs are created, evolved, and sustained. While participants engage in creative activity and construct new meanings, these activities and meanings are closely tied to the technical platforms, code, and corporate policies of CGVWs. Changes in platforms, code, or policies may produce measurable changes in participant activity (Lanzara 2010; Nardi and Kallinikos, 2010; Nardi 2010).

Experience in virtual spaces is embodied, both corporeally and through a complex relationship with an avatar (Boellstorff; 2008; Consalvo & Harper, 2009; Nardi 2010, Pearce, 2009). As in offline life, forms of stratification and hierarchy are persistent features of online life and communities. Debate and conflict regularly occur within communities about what constitutes appropriate behavior, notions of deviance, as well as systems of inclusion and exclusion. Relationships between people via virtual space, even within what appears to be a simple "first person shooter" game, are very complex with a wide diversity of speech categories and elaborate meanings generated in player behavior (Wright, Briedenbach, and Boria 2002; Ducheneaut and Moore 2004; Wright 2012). Consequently, it is increasingly common to find ABS researchers embodied as online avatars during the research studies (see Figure 1).

Figure 1. Images of anthropologists Tom Boellstorff (left) and Bonnie Nardi (right) embodied as avatars in different virtual worlds: *Second Life* for Boellstorff; *World of Warcraft* for Nardi.

Researchers have likewise explored how particular gendered, raced, and classed representations are materialized in virtual spaces, despite opportunities to experiment with different presentations of self (Dumitrica & Gaden, 2009). Likewise, players and scholars have increasingly recognized the global nature of such spaces (Chee 2006; Kow and Nardi, 2010; Nardi, 2010). For computer games this is reflected in business structures, and processes such as localization, which bring together questions of culture and global communication (Consalvo, 2006). In virtual worlds, individuals from multiple countries, cultures, and regions are situated in the same spaces, offering the potential for both cultural misunderstandings and appreciation to occur. Thus we know of the racism that follows the entry of gold farmers in some computer games, as well as the western players of Japanese MMOGs who use virtual worlds as a space to learn more about another country and its citizens (Nardi and Kow, 2010; Nakamura, 2009).

Scholars have found that CGVW activity is highly situated, being the result of particular types of people coming into contact with specific software affordances and game mechanics. For example, Pearce (2009) found that the play community from the virtual world *Uru*, upon becoming refugees when their world shut down, worked together to build new spaces within *Second Life* and *There.com*, which both echoed and transformed their original experiences. Likewise, although heavy players of both MMOGs and casual games invest great amounts of time and capital in their activities, they have very different conceptualizations of the role of games in their lives, and how that activity is central (or not) to their identities (Begy & Consalvo, 2010).

New contexts for the use of CGVWs are emerging, including social network sites, mobile devices, and physical sites for co-located professional and recreational play (e.g., Taylor 2012). Consider, for example, socialized game play now also occurs in larger-scale venues outside the home or arcade, within game play festivals such as *Blizzcon or QuakeCon* (see Figure 2) in the U.S. or their global counterparts (Figure 3), independent or corporate-sponsored game development competitions (“game jams”), or in professional game play competition showcases emerging under the label of “e-sports” such as the *World Cyber Games* (see Figure 4).

Figure 2. A partial view of thousands of game players who brought their personal computers to join in the annual *Quakecon* meeting, held every summer in Dallas, Texas.

Figure 3. A large-scale game play festival in Germany.

Figure 4. An e-sports event with large audiences able to observe competitive game play projected onto large-format displays.

Alongside those changes, we continue to grapple with the way technologies are actors in such spaces, often carrying with them powerful political, ethical and social mechanisms. Finally, researchers have been active in re-assessing the methods used to study players, play spaces, and larger social and cultural contexts. Millions of people now routinely play and interact within CGVWs, the vast majority are under 25 years old, and more than half are under age 15 (KZero 2012). The socio-technical worlds of CGVWs are emerging as a kind of social movement associated with the advance on new computing technologies within and across organizations, institutions, and nation states (Scacchi 2008). Consequently, new qualitative and quantitative methods have been and continue to need to be developed and adapted to capture the complexities of play, as well as individual and group behavior in virtual worlds, and their embedding social and physical worlds.

Research problems

A scientifically diverse set of research problem areas for ABS studies is emerging around new accounts of play, cultures of commitment, developing methodological approaches for how best to study CGVWs, new practices and platforms, producing experiences and co-creativity in CGVWs. Each is described in turn.

New accounts of play

Studying the meanings of play activity for social communities has a long history in cultural anthropology (e.g., Geertz, 1977; Turner, (1982), Sutton-Smith (2001)), in cultural history beginning with the work of Huizinga (1955), and in sociology Caillois (1958/2001). Rather than conceptualizing play as inferior to “work” or production, it is understood that play is productive in its own right. For example, Hendricks (2006) offers an updated approach to understanding the significance of play, by showing play as critical to creative expression in individuals and communities. This aspect of creative expression, fundamental to the development of art and culture in society, provides a foundation for innovation in all areas of social life (Sutton-Smith, 2001). Play as a productive activity allows us to formulate alternate ways of doing things outside of traditional approaches in all areas of everyday life, as well as to simulate and rehearse imaginative scenarios.

As an immersive activity, play ties groups and individuals to a focused activity where reward systems are often immediate and goals may be shifted in the process. Such activity generates emotional engagement, serving as a foundation for establishing meaning in social action—action that can either reproduce existing social hierarchies of power or conversely subvert such hierarchies. Games are one aspect of this larger process of play. However, the expanding structure of immediate rewards found in the organization of games is spreading throughout society (e.g., the “gamification” of everyday life) as illustrated by Castronova (2005), Zichermann (2010), and others (Gamification Wiki 2012).

In CGVWs, then, it is the online world context which provides the new spaces for play, and which afford us an opportunity to observe how players negotiate conflicts over game resources, and resolve issues of identity difference, and develop new ways to cooperate through their differences. Developing new accounts of play is therefore essential to place CGVWs into the broader social-political context of a rapidly changing world.

Relevant projects could include:

- investigating how CGVW play affects group interactions and rewards when conducting in-game activities.
- examining how CGVW play reproduces existing hierarchies of power through visual representations as well as player behavior in “locking” out players perceived as undesirable.
- drawing upon player accounts of game play meaning to see how immersion affects emotional reactions to stress.

Cultures of commitment

One of the challenges in studying CGVWs is that it is easy to slip into a language of “fun,” rather than of “work,” when talking about experience in these spaces. Participants themselves of course invoke this terminology, but often with more nuanced meanings and practices behind use of the term. Slowly but surely we are moving beyond ideas that we can delimit time with CGVWs as “simply” play or just “fun.” There is a growing recognition that more needs to be done to understand focused and passionate engagement with these spaces in terms of notions of “serious leisure,” intense commitment, and even professionalization (cf. Taylor 2012). This counters a rhetoric of “addiction” and focuses attention on the non-pathological but focused dedication people can bring to their time in CGVWs. Analyzing this aspect can also help us understand feelings of obligation or even work-like attitudes often adopted in these spaces. It can also help illuminate the serious labor of how people engage in understanding systems, how they maximize “gaming” them, and the practices for how people collectively produce such knowledge. It is important to note that this issue, perhaps counter-intuitively, can actually also touch on play typically deemed “social” or “casual” (for example with people who spend large numbers of hours playing “casual” games, hanging out in virtual worlds, or being dedicated Facebook gamers).

Relevant questions could include:

- how do users experience a transition from novice-ness to “serious leisure” (e.g., a play-career trajectory)?
- how do social practice and organization within CGVWs develop and reflect cultures of commitment?
- how are CGVWs increasingly the sites for compensated labor?
- what new forms of peer-learning and knowledge-sharing practices are emerging from CGVW cultures?
- under what conditions and situations does game-based play become work, and similarly when and how does work of using virtual worlds become play?

Developing methodological approaches for CGWV

While there is an important history of research in CGVWs going back to the 1980s, it is very much an emerging field of inquiry, particularly given the rapid growth in CGVWs since 2005. As a result, there is a need to develop more refined methodological approaches, as we describe in greater detail elsewhere (Boellstorff et al 2012).

A key point of departure is that the development of methods must take into account the CGVWs being studied and the research questions driving the inquiries. Research methods need to be keyed to the research questions at hand, rather than determined beforehand. Given the fact that CGVWs are places of social interaction in their own right, and are also integrated into physical-world sociality in a range of ways (including group play and the use of consoles and mobile devices), there is a need to develop and deploy ethnographic approaches for the study of CGVWs.

An assumption that quantitative methods are more scientific than qualitative methods, and that qualitative methods are merely anecdotal or illustrative, has significantly limited the range of questions researchers have been able to ask about CGVWs. As a result, it is important to support research and social infrastructure projects that treat qualitative and quantitative methods as equally valid, and develop “mixed methods” protocols that do not treat qualitative methods as functioning primarily to confirm quantitative research. All research methods have strengths and weaknesses, and this should motivate collaborative and comparative work.

Thus, we advocate disciplinary diversity, embracing qualitative, quantitative, and hybrid research methods. The study of CGVWs is inherently interdisciplinary, yet at the present time, the majority of CGVW research funding originates in computer science. This creates a disciplinary bias and tends to exclude some research questions and methods. We recommend a broader approach, in which CGVW research funding priorities are framed beyond computer science, through other disciplines such as the social sciences, the humanities, the arts, as well as health and education.

As this field of inquiry continues to build upon prior work, it will grow in multiple directions. In terms of the form CGVW research takes, three general approaches are: (a) studying a single CGVW; (b) studying multiple CGVWs; and (c) studying virtual world/physical world interactions (Boellstorff 2010). All three of these approaches are valid and respond to different kinds of research questions (cf. Boellstorff et al. 2012).

It is particularly important to encourage comparative work. There are many dimensions of comparison including national cultures, platforms, and varying participant demographics. In disciplines where qualitative methods are well-established (for instance, cultural anthropology), effective procedures already exist for forms of comparative analysis and generalization based on qualitative methods, and developing such procedures for CGVWs should be a priority.

Questions of permission to conduct research are crucial to any discussion of methods. For many researchers studying CGVWs, campus Institutional Review Boards (IRBs) can present a challenge to conducting research. While IRBs are increasingly educated regarding qualitative research, some remain ill-equipped to understand such research, particularly regarding CGVWs. Developing materials and protocols for educating IRBs would thus help advance the scientific mission of CGVW research.

Aside from IRBs, questions of ethics are important to research in CGVWs. Such questions range from ethical qualitative research by investigators who spend long amounts of time participating in CGCW, to the ethics of large-scale quantitative data collection and analysis.

Practices and platforms

CGVW research could benefit from a broadening, diversification, and more heterogeneous approach across a number of areas, including study populations, platforms, and genres.

The populations of players studied in CGVWs are often inadvertently biased by contextual or platform choices, excluding players on the basis of race, class, gender, culture, age, or ability. For instance, the vast majority of multiplayer game research is PC-based, which inadvertently excludes certain minorities, whose network gaming practices tend to be more console-based. In single-player game research, portable platforms, preferred in many low-income communities and among players in underdeveloped countries, are often excluded in favor of consoles. Older players and cross-generational play are also understudied areas. Targeting specific understudied audiences will help expand our understanding of the impact of CGVWs, and a broader choice of games, platforms, and genres will help to promote diversification. Additionally, cultures outside the US are often neglected, and recent findings by Kow and Nardi (2009), Nardi and Kow (2010), Chee (2006) and others show that gaming practices can be quite different in other countries and cultures, even within the same game. In addition, new social forms are emerging out of CGVW cultures in both the US and abroad that warrant further studies: this includes forum groups and peer-based teams that may fall outside the traditional definitions of “community” or “participatory culture.”

Diversification also suggests more comparative studies. By and large, CGVW research takes place within or around a single game or virtual world and within a single culture. Comparative studies of different groups (gender, class, culture, age) playing the same game, or comparisons between games or even game genres (such as across virtual worlds and multiplayer games) would be of tremendous value. Platform heterogeneity within a given individual and demographic also warrants further study: gamers play multiple game genres on multiple devices, and we know very little about the full complement of play practices across multiple CGVWs or platforms (see Paul, 2009a). Because expertise in specific games and genres can and should be highly focused, comparative studies would, by necessity, require larger teams and multiple institutions using parallel or complementary methods to create a broader picture of CGVW culture and practices. Questions include:

- how do players engage CGVWs offline, or engage alternative reality games played across physically located venues as well as on the computer?

- who is playing these games? Are there differences in the gaming communities and identities of players who chose to play these games? What do any potential differences indicate about the play and practices in these CGVWs?

- what impacts do these platforms for play have on networked culture, the home, and daily life for players?

- what are the differences in activity between game-based and socially-based online spaces?

- how do players from different cultures engage with the same game?

- how does game play emerge or be guided to become a professional endeavor and line of work for highly committed game players (Taylor 2012)?

Potential research projects in the area could address the practices of players of any of a variety of different console or mobile phone games, the role of these devices in the daily lives of those who use them, the transformative impacts of these CGVW and devices on the home, and the network cultures produced by the integration of Internet access and online play into these games. Comparative studies could include multiple researchers and institutions to study behavioral and social phenomena across games and cultures.

The online computer itself is not the sole realm for CGVW play or experience, so analysis of the field needs to move to engage all forms of engagement with, through, or around CGVWs. Doing so opens the opportunity to witness diverse practices and a diverse population of people engaging those CGVWs.

Producing experience

While CGVWs are typically commercial products, the experience of participants in these spaces is produced via a complex assemblage of people and things stretching beyond corporate designers and the code in the officially-distributed software artifact. Elements within an assemblage can include:

- corporate entities that design and distribute CGVWs as well as related commercial forums, websites, repositories and the like;
- diverse communities of participants;
- specialized influential teams or communities such as developers of third party viewers in *Second Life*, modders in *World of Warcraft*, or the *Elder Scrolls* series;
- software artifacts/technologies; and
- the larger cultures, institutions, and governance structures within which experience is produced.

How do these entities encounter one another, as they bump up against each other's domains of development and practice? How are claims of expertise and authority asserted, and challenged? While sometimes there is explicit negotiation, very often there is not, and instead formal and lay design communities struggle over terrain and practices. How is the production of experience shaped and contested? Should CGVW companies encourage and support the development of specialized teams and communities? How do systems of national governance, including formulations of intellectual property and censorship, shape CGVW experience? What is the relationship between local cultures (norms and practices) and game mechanics? Do hybrid systems emerge or is it the case that "code is law"?

These questions require theorizing experience (see Day and Ekbia 2010) as well as the mediating influences of the individual elements in the assemblages (see Kow and Nardi 2010; Lanzara 2010, Taylor 2009, Paul 2010). "Experience" is a more expansive and potentially productive concept than "behavior." Experience centers on subjectivities engaged in flows of activities in particular contexts both large and small (Day and Ekbia 2010). Issues of governance, ideology, design, identity, resistance, and the technical evolution of the CGVWs are pertinent.

These issues are especially interesting—and difficult—in the context of CGVWs because of the richness of the assemblages that constitute them, as well as still-emerging concepts of "virtual," "real," and "actual" about which ABS theorists do not agree. The study of assemblages may include multi-site ethnographic inquiry in which each element in the assemblage is identified and examined, first individually and then in relation to other elements, both within and across study sites. Textual analysis of documents produced by elements in the assemblage is another approach. The development of models of experience and mediation will enable us to understand the impact of CGVWs on culture and society.

Co-creativity in CGVWs

Users are active, engaged, meaning makers who construct through creative practices and norms things in CGVW's that often go well beyond designer intent. Formal design increasingly recognizes the "remix" nature of CGVWs, taking into account creative user engagement and often incorporating user-produced artifacts into official releases of software. CGVWs have a long history of being spaces deeply structured via this co-creation via "modding" (Kow and Nardi 2009, 2010, Scacchi 2010, 2011, Sihoven 2009, Sotamaa 2010, Steinkuehler and Johnson 2008). More needs to be done examining this circuit of production. Relevant questions could include:

- how are designers formally incorporating user-developed productions and "mods" into official software releases?
- what models of institutional organization around design are being constructed in relation to co-creative practices?
- what systems of support, and what hindrances, do CGVW companies face when dealing with user-production in their spaces? This could include everything from concerns about intellectual property to organizational structure and institutional communication.
- when users produce modifications to games that are in conflict with designer intentions, how are these situations managed?
- what inequalities exist across different participant populations in terms of ease of co-creation?

Future research infrastructure requirements

Different kinds of ABS research depend on different kinds of infrastructure in order to reach exceptional findings that push the study of a field to a higher level. To answer the research questions raised in this chapter, three primary investments need to be made.

The primary need identified here is to develop a sophisticated social infrastructure to enable a community of scholars to expand the map of our understanding of CGVWs. Quite simply, the questions raised in this report will not be answered by building complex physical mechanisms or other expensive devices, but they will be answered by investing in researchers and their ability to access each other. By investing in building a research community of ABS scholars, the expertise of those in the field can be magnified, expanding our knowledge about CGVWs and answering crucial questions about the dynamics found within them. Primary means by which to build this community of ABS scholars would be to:

- develop research methods workshop or online Wiki for CGVW researchers to discuss and share best practices and successful research methods across CGVWs.
- organized workshops to bring people together across CGVW research disciplines to facilitate sharing across research objects, enabling cross-CGVW analysis and a greater understanding about what is special in any given CGVW.
- synchronizing or phasing of research projects to enable more sophisticated coverage of specific CGVWs or the practices across multiple CGVWs.
- enabling multi-group and multi-site teams to study similar phenomena across multiple CGVWs.

This type of community would offer a number of benefits to the NSF, to the study of CGVWs, and to other CGVW researchers working in the sciences, arts, and humanities indicated in this overall report. For the NSF, this would offer a large community of interested, engaged scholars and both a broad and deep understanding of the practices and dynamics of CGVW. That community would be able to address emerging issues in a rapidly changing field of study, facilitating a key role for the NSF in the study of CGVWs.

These kinds of opportunities would also likely be the best means by which to obtain knowledge about the diverse practices and behavior across CGVWs, especially because of the immense amount of time and work mastery of a single CGVW requires. In addition, a strong social infrastructure would enable a means by which to ensure that comparative work is consistent, aiding in development of research norms in the study of CGVWs.

To support the social infrastructure that is crucially necessary, support for preservation of artifacts and additional modes of dissemination would greatly enhance the study of CGVWs. The transitory tendency of many CGVWs makes developing modes of preserving artifacts like chat-logs, screenshots, video and audio recordings, and a variety of other research artifacts a key need for researchers in CGVWs.

Publication and promotion of key work is also a need area, as quality research into CGVWs is currently dependent on either the good will of journals address to methodological interests or on small publications with a dedicated focus on CGVWs. Expanding the means by which to disseminate work, through journals, workshops, online publications, conferences, or the like, would greatly enhance the ability to maximize the value of the quality work that could be produced in the study of CGVW.

Broader impacts

In North America, people now spend more time with online games than email. The average age of those playing computer games is 30 years old (ESA 2012). CGVWs are spaces for social interaction, education, intercultural exchange, business, and military and governmental activities, as shown throughout this Workshop report. The educational and health impact of CGVWs can be seen in their growing presence in schools, hospitals, and retirement facilities. Formalized spaces such as the New York *Quest to Learn* school, and *Chicago Quest* charter school, use games as an integral part of the curriculum, both in building and using games as sites for exploration, education and learning (cf. Barab et al 2011, Jackson 2011). Virtual worlds support therapeutic interventions such as the virtual world *InWorld Solutions* which is designed as a therapeutic environment for clients such as drug addicts, prisoners, and people with autism spectrum disorders. Game and virtual world spaces are global, with citizens interacting across cultures, languages, and local contexts. Continued study of such activities and sites is central to learning how groups interact with one another, and how culture is constituted, manipulated, and transformed. We must continue and deepen our studies of such activities and spaces to truly understand their impacts on a globalizing culture and society.

Game-like elements are now spreading beyond the boundaries of games and virtual worlds, such as the use of “check-ins” and points awarded for frequenting particular businesses via sites or spaces such as *Yelp* and *Four Square*. Pervasive games and alternate reality games integrate game play into “real life” and games and game-like approaches are being used for increasingly “non-play” applications such as education and military training. This gamification of life that scholars and industry practitioners have remarked upon is not well understood. We need to investigate how such elements might alter or transform daily life, with those working in the social sciences and humanities best positioned to study this transformation.

In closing, we believe this is a key moment for the study of CGVWs. Expansion of NSF and other government funding into building key elements of social infrastructure, preservation of artifacts, and modes of dissemination could substantially expand our ability to answer key research questions about the dynamics of CGVWs and their impact on individuals and societies.

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5. Education & Learning with Computer Games and Virtual Worlds

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Introduction

Although electronic games have been used in the service of learning since the early eighties, today's CGVWs offer new opportunities for education that are still largely unrealized. Unlike the earlier generations of drill-based "edutainment" games (Ito 2007; Ito 2009), today's learning environments offer rich and evolving simulated virtual worlds (Clarke et al, 2006; Clark et al, 2009, Kafai and Fefferman 2010, Ketelhut et al, 2010; Metcalf *et al.*, 2010, 2011) as well as opportunities for players to modify and produce their own games and game elements (e.g., Barab *et al.*, 2007; Barab *et al.*, 2009; Dede, 2009; Gee 2003; Kafai, 2006; Shaffer 2005; Squire 2006; Steinkuehler and Johnson 2008). In addition, today's net-savvy young people and the Web 2.0 environment enable communication and sharing among players and game makers, fostering a social learning environment that supports new forms of peer-based learning and mentorship (Gee and Hayes 2010; Ito *et al.* 2009; Ito and Bittanti 2009; Ito *et al.* 2008).

Building on these new social and technical affordances, current CGVW research and development revitalizes longstanding efforts to use computer games to bridge the gap between formal and informal learning and between educational and entertainment genres. The combination of social media, accessible tools for digital production, and adaptable virtual and gaming worlds offers tremendous possibilities for finally realizing the potential of games and simulations to support meaningful, interest-driven, and learning-centered education. Games and virtual worlds provide an opportunity for more traditional forms of learning and drills (which is now well-established in instructional software), as well as for enhancing technical literacy and capacities for innovation and adaptive learning that are crucial to success in a highly volatile 21st century work environment. These latter sets of skills and capacities are uniquely supported by state-of-the-art social media and virtual worlds technologies, and need to be the focus of more extensive research and development.

The application of information technology to the very core of business operations has caused a profound change in the needed skills and talents of New Economy workers (OECD, 2004). Markets in the New Economy are rewarding those who have high educational achievement and technical skill (Task Force on the Future of American Innovation, 2005); even more so in the current climate of economic realignment. Tomorrow's workers must be prepared to shift jobs and careers more frequently, to be flexible and adaptable in acquiring job skills, and to integrate and focus a changing mix of job-derived and education-based knowledge on business processes and problems (Friedman, 2005). Students who are in the eighth grade in 2012 will be looking for jobs in either 4 or 8 years, depending on whether or not they go to college. Between 2002 and 2012, we have seen a major growth in technology and expect to see even further advancement in the next eight years. The worker of the 21st century must have science and mathematics skills, creativity, fluency in information and communication technologies, and the ability to solve complex problems and adapt to shifting technologies. (Business-Higher Education Forum, 2005, Honey and Hilton 2011)

However, on the 2006 Program for International Student Assessment (PISA), U.S. students performed the lowest in areas around the problem solving aspects of inquiry (Organisation for Economic Co-operation and Development, 2007). Numerous reports, such as the National Education Technology Plan (NETP, 2010) and the National Academy of Science's Learning Science through Games and Simulations (Honey and Hilton 2011) emphasize a focus on interdisciplinary content that links domains such as literacy and science rather than treat them as separate disciplines. Further, critical thinking, complex problem solving, higher-order thinking skills, collaboration, and technology fluency are competencies that need to be woven into all content areas such as, literacy, history, music, art, even military defense (DAU 2005), and not just STEM (e.g., Richter 2011). The United States is falling behind the rest of the world in academic achievement and graduation rates (NETP, 2010). Computer Games and Virtual Worlds have the potential to provide interdisciplinary learning experiences that provide students with the kinds of skills students will need in the changing economy. Realizing this potential requires targeted and strategic support for research, development, and dissemination of new models of game-based learning that are keyed to the contemporary networked and new media environment.

Current Findings

Existing research on learning with contemporary CGVWs tends to be split between studies that look at the in-school and out of school context. (Hirumi 2010, Honey and Hilton 2011) There is widespread agreement that CGVW play a significant role in children and young people's lives, and a number of descriptive studies have documented the time that young people and adults devote to game play, the kinds of games they play, and the game-related practices that they pursue (e.g., Lenhardt *et al.*, 2008). Those who study the learning dimensions of commercial and entertainment-oriented games have argued that games are in many ways ideal learning technologies, providing feedback and challenge that is keyed to the individual player's abilities, interests, and motivations (Gee 2003; Shaffer 2005; Squire 2006; Steinkuehler 2008). Studies of CGVW communities and everyday play have demonstrated how games become sites of peer-based knowledge exchange and creativity that enable young people to develop expertise, literacy, and communication skills within a dynamic social environment (Gee and Hayes 2010, Ito 2006, Ito 2007b, Ito and Bittanti 2009, Steinkuehler 2008).

Studies of game play within explicitly educational contexts have had mixed results, in part because of the considerable diversity in the kinds of CGVWs that have been studied, and due to limitations in the research designs (Tobias & Fletcher, 2007). However, a growing body of research on CGVWs designed for K-12 education has been found to enhance participation in science-based activities while promoting socially responsive behavior (Hirumi 2010, Kafai, 2006), to inculcate social and moral development via cultures of enrichment (Barab *et al.*, 2005), to foster computer programming and collaboration (Bruckman, 1997), to engage interest in math (Elliott, 2005), to support understanding of causal complexity (Metcalf *et al.*, 2010), and to develop inquiry skills (Nelson, et al, 2005; Clarke *et al.*, 2006).

River City, *Quest Atlantis* (Figure 1), and *EcoMUVE* (Figure 2), all originally funded by NSF, are the only educational VWs that have been studied extensively in formal educational settings, over a number of design iterations, and brought to scale (Clarke & Dede, 2009, Dieterle 2010, Metcalf et al 2011). Studies such as these have shown that CGVWs can support learning in the domains of scientific reasoning, problem-solving, literacy acquisition, and pro-social behaviors (Barab *et al.*, 2005, Clarke *et al.*, 2006, Ketelhut, 2007, Nelson, 2007, Dede, 2009, Steinkuehler 2008).

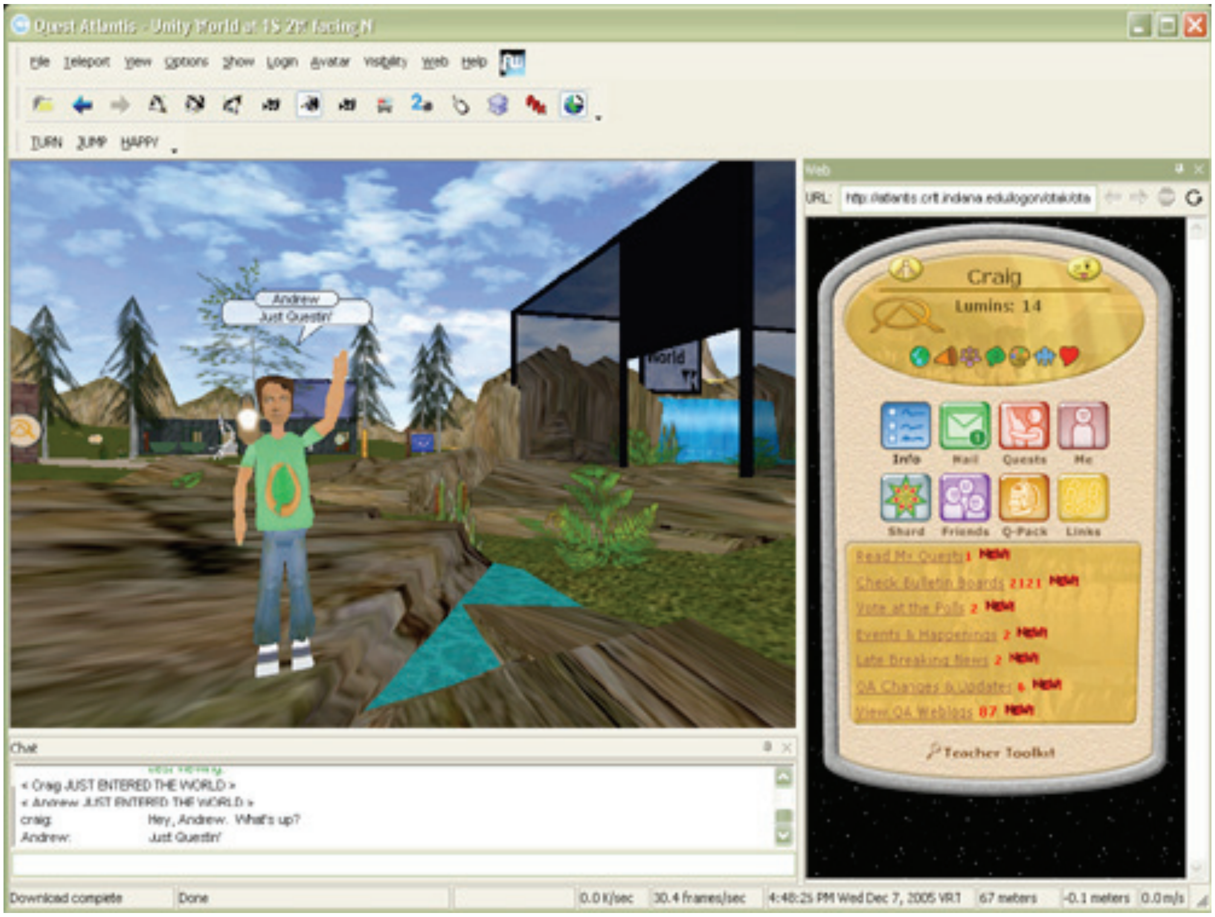

Figure 1. A screenshot from *Quest Atlantis.*

Other efforts supported by private foundations have invested in the development of learning games suitable for use in formal or informal settings, with emphasis targeting new skills like computational thinking [Wing 2006] for intermediate or secondary school students. The MacArthur Foundation invested in game development framework like *GameStar Mechanic*, shown in Figure 3. Other corporate sponsors and non-government organizations have invested in STEM game development competitions like the *National STEM Game Challenge* (see Figure 4) (www.stemchallenge.org), which encourage middle and high school students and teachers to get involved in game development as a way to enhance their computational thinking skills. While the games that results from these frameworks or competitions are often modest, their purpose is not to encourage students or teachers to produce commercially viable games, but instead to encourage the learning and practice of computational skills and reasoning abilities.

In contrast to these efforts targeted to formal education settings, other CGVWs have been developed and deployed in settings targeting informal education. In such settings, free-choice for what to play or experience, along with little/no prior preparation/instruction must be accommodated, as well as how to provide informal learning experiences for potentially large or very large number of players (>100K per year) who play within small family or student groups.

Figure 2. A screenshot of *EcoMUVE*, an educational VW designed to advance ecosystems science education via situated learning within a group of users (students).

Furthermore, CGVWs are being developed and deployed in hands-on regional science centers or museums that feature interactive experiences. For example, The Field Museum in Chicago (Aronowsky et al 2011), and the Discovery Science Center in Santa Ana, CA (see Figures 5 and 6; also Scacchi et al 2008, Scacchi 2010) have invested in research, development, and deployment of CGVW-based learning experiences that provide either onsite CGVW-based interactive exhibits (DSC), online science learning games (DSC, Field), or both—interoperating exhibits and online games (DSC). These informal science learning environments within the science centers are designed to deliver active, embodied learning experiences that are tied to state and/or National Science Education Standards. Consequently, onsite signage, handouts, or other exhibit affordances must guide visitors/learners into grade, skill-level, or subject matter relevant experiences through hands-on interactivity. Also noteworthy is that interactive experiences within regional science centers often realize a learning opportunity for parents and teachers who may have forgotten or studied little about science topics during their formal education during their student years. So CGVWs can provide the potential for young students and adults to learn STEM subjects (or other academic subjects) together as a family activity.

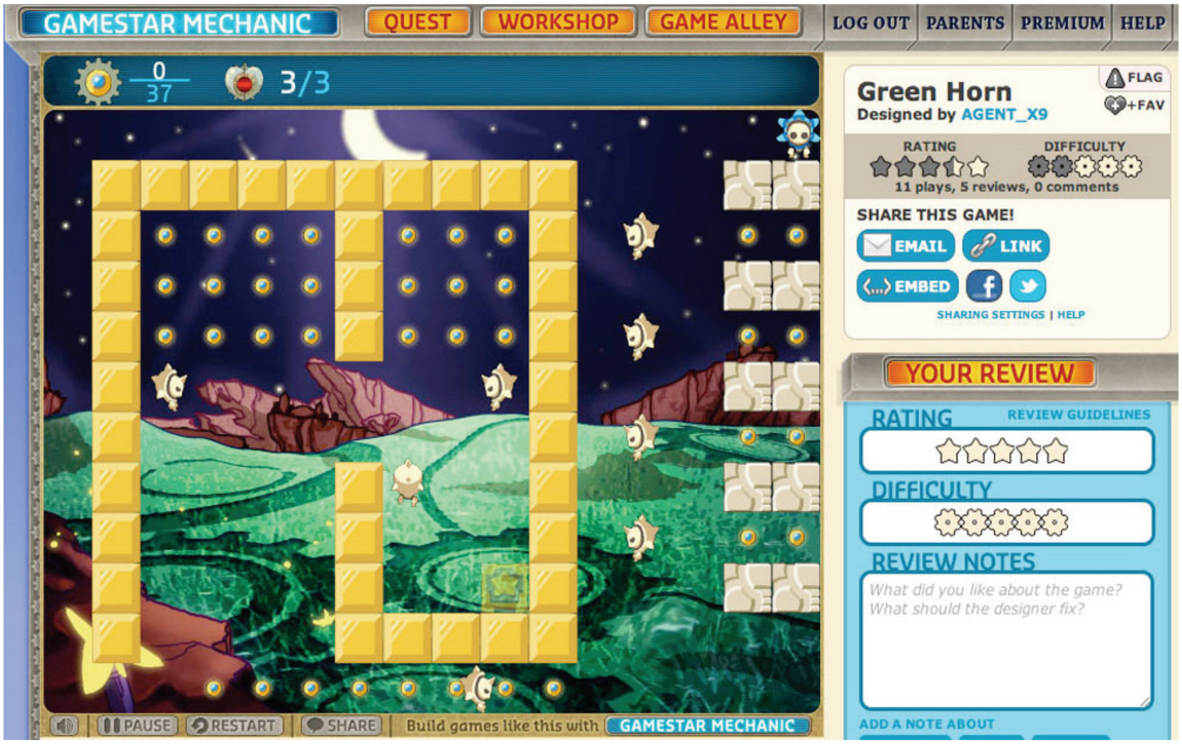

Figure 3. A screenshot of a student developed game created with *GameStar Mechanic*.

Figure 4. The STEM game design competition (http://www.stemchallenge.org/about).

Figure 5. An in-game view of the research collaboratory and video-based avatars in Web-based, free-to-play, *DinoQuest Online* science learning game (http://www.dqonline.org).

Figure 6. Onsite, physically embodied and family-friendly science game play in the *DinoQuest* exhibit at the Discovery Science Center.

Last, there are also studies that examine how commercially available games for entertainment are being used, modified, or adapted to provide educational experiences in either formal or informal settings (e.g., Gee 2003, Gee and Hayes 2010, Hirumi 2010, Honey and Hilton 2011, Ito 2007a, 2009, Kafai and Fefferman 2010, Steinkuehler 2008). Here research results point to the potential of CGVWs to provide next-generation learning environments that can realize transformative learning experiences that meet or exceed the standards of practice currently found in formal education settings. The challenge remains for how best to realize this potential given the conditions and institutional arrangements that currently frame and control educational curriculum and teaching practices.

While game-based learning in both informal and formal contexts shows considerable promise, we see relatively few research and development efforts that bridge this divide, and bring the interest-driven and peer-based context of recreational gaming to bear on more explicitly educational forms of play. On the informal side, the learning potential of CGVWs suffers from lack of focus on academic and pro-social outcomes. On the formal side, we see limits to CGVW's influence and impact because most efforts are restricted to small, experimental educational programs and have not scaled to reach the large numbers of young people comparable to those who participate in the commercial and recreational gaming space. A successful research and development program in CGVW for learning demands that we bridge this divide between educational and entertainment oriented gaming contexts. This requires an integrated approach to empirical research, design, and dissemination that centers on the current opportunities afforded by state-of-the-art games, virtual worlds, and networked social media.

Research Problems

We have identified five key areas for further research and development efforts that explore the use of CGVW for learning. These areas are briefly described below.

Broader conceptions of learning outcomes

Research on CGVW needs to clearly identify and address a broad spectrum of desirable learning outcomes. These outcomes should go beyond traditional conceptions of academic achievement and content acquisition to include social, ethical, interdisciplinary, and creative abilities, knowledge, and practices. We also need research that better differentiates among different kinds of games and virtual worlds, and their respective strengths and limitations for achieving various kinds of educational goals. For example, "computer games' can include everything from Facebook "social" games like *Farmville* to simulations such as *SimCity* to games that involve players in game design itself such as *Little Big Planet, Minecraft*, *Jumala* and *Roblox*. In addition, CGVW are increasingly played on platforms beyond the traditional desktop computer or game consoles; hand-held devices and mobile phones can now support sophisticated gaming technologies while freeing players to move among different physical environments; the addition of motion-sensing technology has led to gaming that engages players in physical as well as mental activities. We know that learning associated with CGVW is not confined to experiences within the virtual environment; social interactions around CGVW, either face-to-face or in online communities, as well as related practices such as modding, making machinima, fan fiction and fan art, and so forth all offer opportunities for learning that must be included in research on the educational potential of these technologies.

Research on the outcomes of CGVW can and should be based on robust theories of learning that incorporate not only cognitive and behavioral change, but also changes in identity, practices, values, and affiliations. While earlier research on CGVW often drew on narrow models such as theories of cognitive processing, more recent work has begun to draw on a wider range of conceptual frameworks that can better account for the social, cultural, and affective dimensions of learning (Federation of American Scientists 2006).

Some broad questions relevant to this area include:

- How can CGVW be used to support learning that transcends traditional disciplinary boundaries?
- How might CGVW be most appropriately integrated into broader educational reform efforts, particularly those aimed at the development of higher order, “21st century skills”?
- How do CGVW support new means of assessing learning? How can more meaningful assessments be incorporated into the design of CGVW?
- How does what is learned through CGVW “transfer” to other sorts of situations and practices? How might CGVW be best designed to facilitate “preparation for future learning” (Bransford & Schwartz 1999)?

Bridging education and entertainment markets and genres

As stated earlier, we see tremendous potential in today’s games, virtual worlds, and social media in supporting education that is highly responsive, interactive, and learner-centered. One of the major challenges in realizing this potential is that the markets and media genres for educational and entertainment media are highly segmented. Young people avoid games with an explicitly educational agenda when they have choices of media at home, and educators shy away from media that have elements of peer sociability and entertainment genres embedded in them. Although learning software has viability as a commercial product for young children and educationally-minded parents, by the time young people start dictating their own media choices, they avoid software and virtual worlds that have an adult-centered learning agenda (Ito 2007a). Prior research has also documented how bringing interactive and computer technology into classrooms alone does not change the culture of a school towards a learner centered mode (Cuban 2003). In other words, infusing academic learning with the fun, sociable, and interactive modalities of CGVW play and online activity requires bridging a formidable culture and market divide (Honey and Hilton 2011).

Addressing this challenge requires more empirical work on the nature of the divides and possible spaces of opportunity, as well as development, outreach, and partnerships that are explicitly targeted towards bridging entertainment and education markets. Potential research questions include:

- What kinds of software products do parents and young people seek for supporting education, and how does this differ from purchasing decisions for entertainment products?
- What do educators look for in software products to use in school?
- What are examples of successes in commercially successful games and virtual worlds with valuable learning outcomes or that have linked in-home media with in-school media?

- What software development and media organizations are innovating in the area of games and virtual worlds for learning, and how might these efforts be linked up to the research community?

Bridging research on learning in and out of school

A third emphasis in our proposed research agenda is bridging the existing divide between research on in-school and out-of-school learning with CGVW. Ironically, the current interest in using CGVW for education is rooted in observations of the features of CGVW that seem to support learning in out-of-school settings, such as their ability to engage players in solving complex and challenging problems, yet often educational CGVW have few of these features. For example, while a number of studies have identified the key role of social interaction in game-related learning (Duncan & Hayes forthcoming; Salen 2007), there has been little if any attention to social context in the design of educational games.

Furthermore, CGVW take many different forms and presumably have quite different affordances for learning, yet the implications of these differences for learning are poorly understood, both in and out of school. In addition, while researchers have begun to document the varied forms of learning that takes place through and around CGVW in out-of-school settings, we know little about the significance of this learning in other contexts of people’s lives, including formal education. From a design perspective, a potential affordance of CGVW is how they can transcend the physical and temporal boundaries of formal education, by increasing student motivation and engagement and through technologies that can be available via the internet and mobile devices beyond the classroom. However, this affordance will not be fully realized without a research and educational infrastructure that transcends the brick and mortar walls of school as well as the invisible but just as solid boundaries of disciplinary knowledge and research.

These divides are further exacerbated by a cultural divide between those who understand (and participate in) popular CGVW culture and those who do not. The discourse and practices of popular entertainment gaming, for example—quests, leveling, modding, cheating, and so forth – are not widely understood or embraced by educators; at the same time, there is a considerable gap between the knowledge and interests of educators and social scientists, and the engineers and computer scientists who are advancing the technical dimensions of CGVW.

An agenda in this area should address the following issues:

- How do different genres of CGVW support different kinds of learning, across the contexts of formal and informal learning?
- How does out-of-school learning associated with CGVW (using the expanded notions of learning outcomes described above) support, inhibit, or otherwise relate to the kinds of academic learning typically emphasized in formal education?
- What are the most promising approaches to designing CGVW that bridge in school and out of school learning?
- What sorts of theories, models and conceptual tools are most useful for developing common understandings of learning associated with CGVW across settings?

Universal Design

Another emphasis in our proposed research agenda is accessibility. The field needs to incorporate designs that are flexible, adaptable, and accessible for all students. One way of ensuring all students have equal access to content, in both formal and informal settings, is to incorporate Universal Design for Learning (UDL) principles (Rose & Mayer, 2000, 2002). These principles guide designs that are more accessible to a large variety of students, including those with special needs and those who are learning English as a second language by providing:

- alternative formats for presenting information;
- alternative means for action and expression; and
- alternative means for engagement.

An agenda in this area should address the following issues:

- how do we design CGVW that are flexible to meet the needs of all students?
- how do we build flexibility and adaptability into the designs of CGVW?
- what types of design features in CGVW provide open designs for a wide range of learners?

Sustainability and scaling of innovation

While public research funding has supported the development of innovative new learning platforms, these experimental efforts are difficult to sustain and scale. A continuing problem in software development is the issue of software obsolescence. The issue is even greater for educational technology, because the materials don't have the backing or resources of business products, nor, in general, the potential for significant commercial profits. Too often we see grant-funded research projects develop powerful and innovative learning tools, demonstrate significant learning gains, receive enthusiastic response from teachers and students, only to founder unused as funding ends, platforms change, servers are unsupported, and software won't run on newer machines. The impact of these efforts is limited to small numbers of students, and we don't see these new systems able to address issues of equity and public access at a systemic level.

As we pursue research in CGVWs for education, we see a strong need for support for outreach and dissemination of current and future research projects that show evidence of efficacy in realizing learning goals. Potential opportunities for addressing this need include the use of extensible and open systems, partnerships with commercial markets, better integration with a systemic public schooling agenda, and a focus on domains like gaming and virtual worlds that are already receiving enormous commercial success. An agenda in this issue should look at how to leverage the power of these environments to create educational tools that harness the accessibility and support that the platforms already provide – and with which students are already particularly familiar. For example:

- what are the bottlenecks that learning-oriented CGVW developers face when they need to upgrade and scale their innovations?

- what kinds of partnerships, at the policy layer and the commercial layer, can help address these bottlenecks?
- are there underlying platforms and standards of interoperability that can help with the problems of scaling and sustainability?

Future Research Infrastructure Requirements

Implementing the kinds of learning experiences made possible via computer games and virtual worlds requires a reliable infrastructure that supports learning in both formal and informal environments. Such infrastructure requires:

- reliable broadband in both school and at home;
- high-end computers capable of running CGVW (requiring sufficient memory, processor speed, video card, network connection);
- support for multi-user interactions;
- advance gaming technologies such as programming scripts and AI that can be shared across projects;
- data and development coordination to facilitate development;
- systems that support scaling both infrastructure and governance (platforms, safety/security issues); and
- funding that is sufficient to support game design.

The entertainment game industry is evolving new production and distribution methods, reflected in the increasing numbers of downloadable games, open source design tools, and server-based games that can dramatically reduce the costs of creating, updating, and distributing CGVW. These methods have promise as models for overcoming some of the cost and customization barriers that currently limit the creation of educational CGVW.

Broader Impacts

Internet-generation students have different expectations for school based on the ubiquity of technology in their lives. A large part of their daily social interactions include social technologies including text messaging, online gaming environments, tweets, and blogs. They take technology for granted—they expect it to be integral to their lives and to serve them, including in education (Campbell, Oblinger, *et al.*, 2007).

Effective educational tools meet these students in the digital world. CGVWs have the power to transform education through engaging, immersive environments that promote skills in higher-order thinking, communication, information processing, and the creativity and flexibility that are essential to our fast-paced, highly technical world (Honey and Hilton 2011).

CGVWs may be a promising complement to more conventional kinds of instruction, particularly for *low-performing students unmotivated by conventional pedagogy, thereby substantially increasing* *the pool of expertise available to the nation* and the sophistication of its citizens in critical thinking skills. In summary, some of the broader impacts that we see as we pursue a research agenda in CGVW include:

- access to rich, meaningful learning opportunities for all students;
- potential for lifelong learning opportunities;
- stronger ties between entertainment and educational games;
- more productive relationships between social scientists, computer scientists, and educational practitioners; and
- stronger links between young people's learning in school and out of school.

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6. Computer Games and Virtual Worlds for Science, Health, Energy, Environment and Defense

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Introduction

Our focus in this chapter is on Computer Games and Virtual Worlds (CGVW) designed to support and enable research and education in the sciences, health, energy, environment, and defense (SHEED) problem domains. It is not about game theory, which is an important approach to mathematical optimization. CGVW are a means for advancing SHEED research and development activities. CGVW are also a means for advancing formal and informal education in science, technology, engineering, and mathematics (STEM) topics, especially those targeting student learners in the K-12 grades. However, we believe that CGVW will increasingly be relevant at the undergraduate, graduate, and post-graduate levels in different SHEED problem domains.

One reason why CGVW are relevant to research and education follows from their potential to realize and deliver a *procedural rhetoric* (Bogost 2007) through play activities. Procedural rhetoric refers to the practice of authoring/expressing arguments through computational processes or CGVW-based models whose enactment seeks to change opinions or actions of players. Such story embodiment, enactment, and experience through game play is an effective method for SHEED education and personal engagement (Doucet and Srinivasan 2010).

Procedural rhetoric is a form of computational thinking that software developers or CGVW designers employ to shape, direct, or control user action with the system. For example, *exergaming*--game play focusing on physical activity by the player—seeks to motivate exercise and human mobility (Lieberman 2006) activities through playful CGVW-based physical engagement. Exergaming has been found to be an effective method for self-managed improvement of personal health through physically embodied play (i.e., games played away from the keyboard and sitting). Augmented reality games (ARG) that link activities in the physical world to their in-game (virtual) counterparts also offer the potential to serve as new ways and means for engaging SHEED processes and practices through playful experience and multi-modal interaction, facilitated via sensing and mobile (e.g., handheld) devices.

Compared to other forms of intervention, CGVWs engage multiple senses of the player. CGVW commonly engage the visual and auditory senses, while ARGs also engage the tactile and potentially other senses. Some networked, multi-player games also provide the capability to interact with other players through speech. Games also engage multiple intelligences by embracing play activities and reasoning about space, body kinesthetics, linguistic ability (especially in surrounding game play discourse), music and spatial sound, and more (Gardner, 1993, 1999). Thus CGVWs have the potential to result in significantly greater positive outcomes in terms of learning, retention and behavior modification.

We believe that CGVW can support research in SHEED domains by: (a) serving as a research platform or testbed for experimentation (simulation based research) that may be open for extension and refinement through open source software or data; (b) serving as a new kind of research instrumentation for collecting and processing concurrent event-driven data through environmental or human-directed sensors; (c) as media for training researchers in emerging tools, techniques, and concepts at the forefront of their research problem domains, and (d) serving as new media for disseminating and publishing SHEED research results.

CGVW technologies embody comparatively little STEM concepts at present. Many incorporate concepts like physical mechanics, simple gravity, and inverse kinematics within a "physics engine," while graphics processors and software routines employ methods for computing various kinds of geometric transformations to synthetic lighting and optical effects in efforts to attain improved visual realism. AI engines that provide a model of computational reasoning or problem-solving intelligence draw from advances in Computer Science. These physics and AI engines and graphics processors are now common as middleware or part of the infrastructure for CGVW. But there are not yet comparable CGVW engines for other widespread physical or natural processes for biology, chemistry, earth systems, energy, nor electro-magnetics, quantum physics or astrophysics, nor even for other kinds of computational or engineering processes.

There is a marked difference in the extent and nature of CGVW use in different SHEED disciplines. For example, use of CGVW in Computer Science is significantly higher than in Engineering disciplines. In CS, CGVW are primarily designed and developed by students as the outcome of their coursework. In the process they learn about practical issues relevant to the creation of CGVWs from a technical standpoint. In engineering disciplines, CGVW are used as tools to facilitate learning and increase motivation and retention in engineering disciplines. This has been attempted primarily through engaging students as players of educational games (Isaacs *et al.* 2008, Srinivasan, *et al.* 2008) and in at least one instance by engaging students as creators of games (Coller). Although the data is limited, the former approach appears to be more suited for a high-school audience while the latter approach appears to be more suited for students in higher education. Thus, looking forward, we anticipate new CGVW for educating college students in topics like the design and analysis of electrical or digital circuits, physical structures, mechanical mechanisms, biomedical device design, aeronautical transport systems, and advanced robotic or nano-technology manufacturing systems, physical activities and devices. Scacchi (2010a), for example, describes a CGVW that models and simulates a semiconductor device fabrication facility, and how it is used to train manufacturing technicians in servicing and diagnosing problematic equipment and potentially hazardous material spills, as well as training proper gowning procedures for working in a cleanroom environment. Such a CGVW can also be readily adapted to support nanotechnology-based or biotechnology fabrication facilities.

Recent studies and findings

Multiple successful science learning games are at hand. Both commercial games like *DroidWorks* from LucasArts (once marketed as a game that satisfies National Science Education Standards), *Race to Mars* by the Discovery Channel Canada, and *Whyville* all embrace and impart STEM principles through informal means. Non-commercial academic games like *Gamestar Mechanic*, *DinoQuest Online, WolfQuest*, *Quest Atlantis, RiverCity* , and *EcoMUVE* all similarly embrace and offer game-based ways and means for achieving STEM education in line with (or beyond) national science education standards. However, these STEM games are targeted to K-12 students, which is a vitally important audience of learners. But we also want to draw attention to learners, practitioners, and the interested public working at the undergraduate, graduate, and professional research levels. Here we see SHEED CGVW-based research efforts are beginning to appear, as indicated by the following set of examples.

To start, the ability to engage in scientific reasoning can serve as a core game play mechanic. Numerous examples abound in formal and informal K-12 grade CGVWs, as indicated in the earlier chapter of Education and Learning. However, undergraduate or graduate level courses can employ games that require players, for example, to produce conjectures and refutations about a new concept, following the methods for establishing new scientific claims originally suggested by Karl Popper (Lieberherr et al 2010). The Specker Challenge Game within Computer Science, also now called Scientific Community Game, demonstrate this style of game play. Other CGVWs focusing on sophisticated reasoning or problem solving in complex domains also exist.

FoldIT (http://fold.it/portal/), is a protein folding game based in the field of proteonomics, allows anyone to download the game to figure out how best to fold or unfold a puzzling protein structure. Recent research indicates that some non-biologist game players outperform both existing computational approaches and biologists (Cooper, *et al.* 2010).

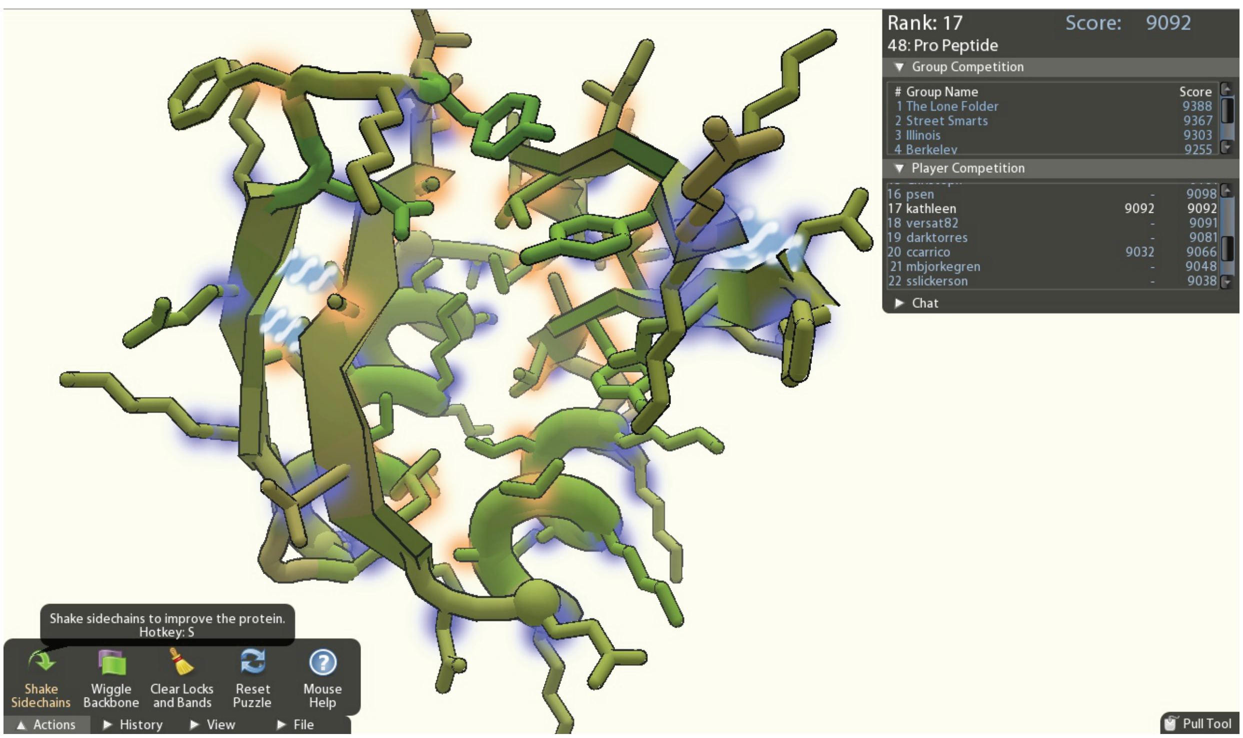

Figure 1. A screenshot from the Fold-IT protein-folding science game.

In a study of laparoscopic surgeons reported in the journal, *Archives of Surgery* (Rosser, et al. 2007), researchers found that surgeons who played computer games before conducting surgical procedures outperformed other surgeons, even those with more experience, in conducting comparable laparoscopic surgeries. The study concludes computer game skills that emphasize fine motor control correlate with laparoscopic surgical skills and improved surgical outcomes. Training curricula that include these kinds of CGVW may help thin the technical interface between surgeons and screen-mediated applications, such as laparoscopic surgery. CGVW may thus be a practical teaching and rehearsal tool to help train/prepare surgeons.

Studies at the University of Rochester (Green, *et al.* 2010) and elsewhere (Rebetez and Betrancourt 2007) find that ongoing, extended play with highly interactive, action-based CGVW improves visual reasoning and problem recognition of subjects. Such capabilities may be relevant for helping to determine which people are particularly well-suited or gifted at performing visually complex or visually coordinated tasks, such as monitoring airplane dashboards and flight controls, or command and control systems for monitoring industrial or public infrastructure systems like nuclear power generation systems.

Current medical research studies in progress at UC Irvine (Takahashi, *et al.* 2008) and elsewhere focus on the use of assistive robotic rehabilitation and therapeutic protocols that employ CGVW game play for patients recovering from strokes, traumatic brain injuries, and spinal cord injuries. Such play gives rise to improved recovery rates and measures for the patients (and therapists), who find the CGVW play highly motivating compared traditional therapeutic procedures. These studies also suggest that deeper reweaving of neurological pathways (i.e., neuroplasticity) may also be occuring as a possible mechanism accounting for measured improvements in physical ability.

The *Visible Human* project (http://www.nlm.nih.gov/research/visible/visible_human.html) from the National Institute of Health helped pioneer the use of computer-based virtual models of human anatomy, along with enabling the creation of a new scientific journal focusing on different kinds of scientific and medical research that are now enabled through such visualization methods. Google also recently announced a new experimental application service called *Google Body* (http://bodybrowser.googlelabs.com/) that provides visual browsing, search, and rendering of human body systems. Could such visible human models be incorporated into future CGVW? Could such models be extended to interoperate with biological or physiological behavior simulations? Will it be possible to eventually re-animate a complete virtual human using scientifically-based behavioral system simulations?

Through extensive surveys of literature on video games that promoted health-related behavior change, (Baranowski et al 2008, Baranowski et al 2011, Barnett et al 2011, Bidiss and Irwin 2011, Lieberman 2001, 2009, RWJF 2008, 2011) along with carefully designed games for use in clinical studies (Thompson et al 2010), consistently find that the video games can produce positive health-related changes. However, variability in the data reported and the evaluation methods employed precluded the linking of outcomes to specific game design characteristics or play experiences. This points to the need for more studies in this area. Correspondingly, there is also a need for development of more CGVWs in the health arena, from those addressing chronic care ailments (obesity, diabetes, asthma, AIDS, ASD, etc) to national health care policy. *SimHealth* is a game from 1994 that simulates the United States health care system, and allows players to make national-scale decisions about health care spending decisions (http://en.wikipedia.org/wiki/SimHealth). Also, in the exergaming category, there are several recent “exergames” like *Wii Fit* (Nintendo, 2008) and *Yourself! Fitness* (http://respondesign.com/history.php, 2004) that merit study of their efficacy to help determine what game design features are most strongly associated with positive health outcomes, such as recovery from injury (WiiHab 2011). Finally, there are also studies that reveal how young people may respond, understand, and then change the way the way the think and act in response to unexpected health care problems like viral epidemics through sustained play in

CGVWs during "virtual epidemics" were players also socialize their in-game viral ailments through the ailment's trajectory, including fear of contagion spread through contact, social isolation, and later re-integration (Kafai 2008, Kafai and Fefferman 2010, Neulight et al 2007).

Figure 2. Scene during the "Whypox" virtual epidemic in Whyville.com, a game-based VW targets at students interested in science, and also online socialization. Chat bubbles display players infected during the epidemic via online sneezing ("achoo"), and close-up view of a player's appearance with Whypox.

Play2Train is a 3D virtual place where geographically separated learners, subject matter experts, and content builders meet as avatars to create collaboratively immersive learning experiences for the health care, emergency preparedness, and educational services industry (http://play2train.hopto.org/).

Next, in the domain of astrophysics, a diverse and geographically dispersed group of leading researchers has formed the Meta-Institute for Computational Astrophysics—MICA (http://www.mica-vw.org) as an online virtual world, *StellaNova* (See Figure 3), that serves as a testbed for 3D astrophysical models and simulations. Additionally, this VW serves as an online place where researchers in this community can meet virtually, socially network, hold interactive research seminars, and engage in public outreach (Djorgovski *et al.* 2009). In particular, they also model and simulate complex astrophysical systems such as galaxy clusters and N-body simulations using 3D modeling and CGVW simulation techniques (Knop, *et al.* 2010). This modeling, simulation, and scientific visualization of complex physical systems is also supported within the *OpenSim Hypergrid* open source software platform, which is similar to the commercially available *Second Life* VW (Henckel and Lopes 2009, Lopes 2009).

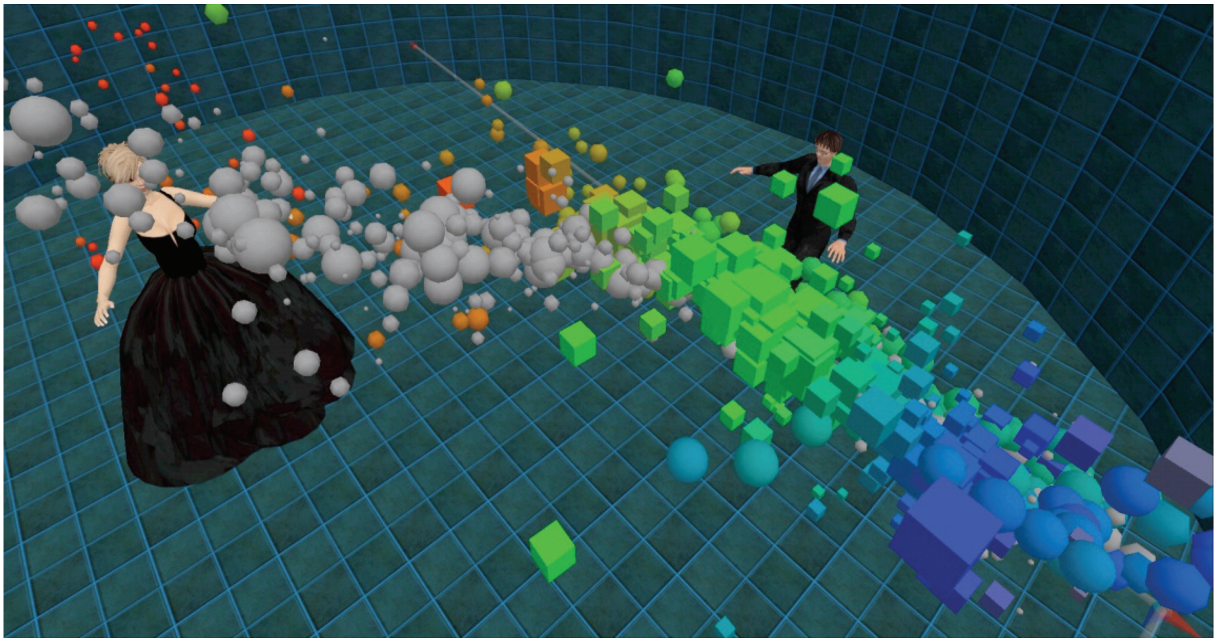

Figure 3. Two MICA scientists in an immersive data visualization experiment, developed by (Djorgovski *et al.* 2009). Data from a digital sky survey are represented in a 6-dimensional parameter space (XYZ coordinates, symbol sizes, shapes, and colors).

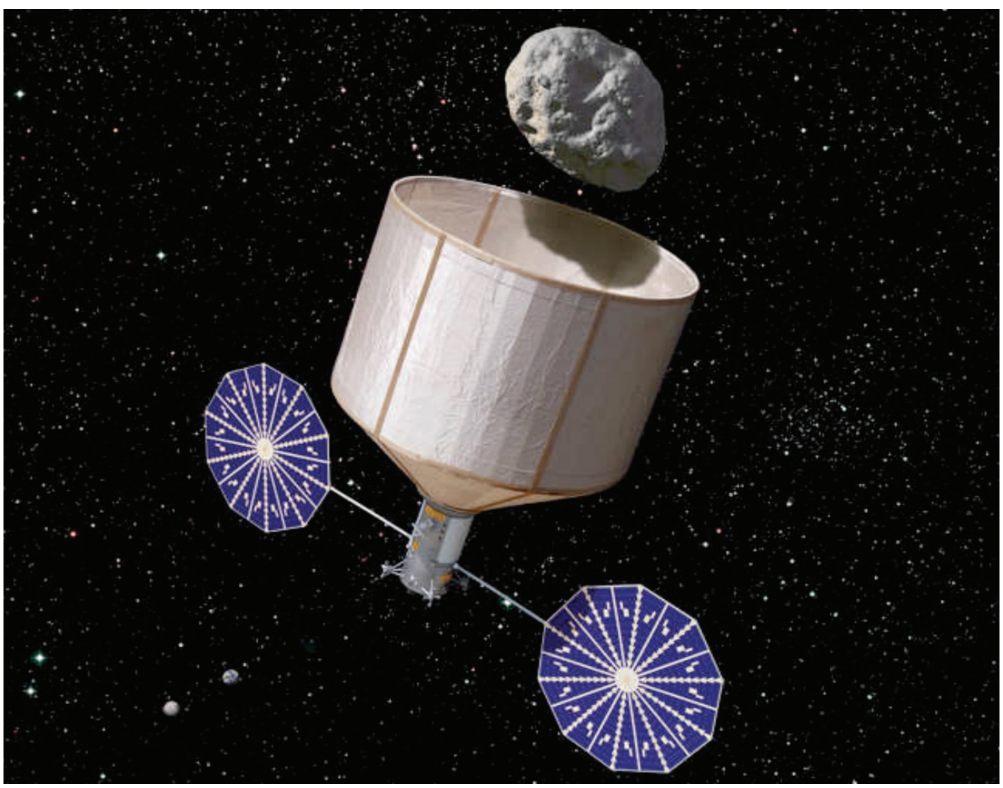

Figure 4. Envisioned robotic space vehicle for capture and spatial transfer of near earth asteroids for resource mining. Image credit, Rick Sternbach (KISS 2012).

Overall, the view at MICA is that VW can serve as an immersive environment for scientific research, scholarship, collegial interaction, and education that offers substantial savings of time and resources, and eliminates a lot of unnecessary travel. However, the challenge of sustaining such as VW remains an open question. Last, recent astronomical exploration studies have outlined the potential for robotic or human travel to near-earth asteroids for the purpose of exploration and resource exploitation that are economically and technically feasible (KISS 2012 – see Figure 4). The ability to model and simulate such future space exploration missions within a game-based VW seems obvious to some, as well as reminiscent of STEM education efforts associated with *Race to Mars* (2011).

Recent research has also investigated how commercially developed CGVWs engage and present topics that are based in other fields of scientific knowledge and practice (Bainbridge 2007, 2010a). Bohanon and colleagues (2010), for example, examined how the popular user-customizable game *Spore* employs evolutionary biology as a framework to “evolve” in-game creatures. They report that models and processes presented are inaccurate, misleading, and inauthentic, such that if consumers rely on such a game to learn about evolutionary processes, their understanding of evolution from a scientific perspective will be wrong and misinformed.

In contrast, Bainbridge (2010b, 2010c) describes two alternative studies where in the first (Bainbridge 2010b) he reports his experience in conducting and participating in a scientific research meeting within *World of Warcraft,* where the participants were both skilled WoW game players, and attended the in-world research meeting through their WoW-based avatar. This effort helped demonstrate that scientific research meetings can be successfully conducted in such a virtual world, without the game distracting or undermining the purpose of the meeting. This in turn has given rise to the development and deployment of a VW within Second Life (called “IISland” see Figure 5) operated by the NSF for the purpose of holding scientific peer review meetings. Consequently, research proposals submitted for consideration and funding by NSF are collaboratively reviewed and discussed among scientists acting through their avatars within the VW of IISland (Bohannon 2011).

Figure 5. Screenshots from the NSF *IISland* VW where scientists meet to conduct peer reviews of research proposals (Bohannon 2011).

In the second study (Bainbridge 2010c), he examined the depiction of science and technology practices and social values within two large game-based worlds, *The Matrix Online* and *Tabala Rasa*. Both game worlds portray scientific and technological practice as moving beyond human control, to a more dystopian vision. However, he finds no evidence to suggest that dystopian worlds or virtual envisionments are any more/less compelling than utopian or mundane physical worlds.

Finally, studies by Duchenaut (2010) and Fox, Kelly, et al. (2010) investigate the potential of conducting different kinds of research studies using CGVWs. Duchenaut for example conducts large-scale social studies of human activity by systematically and automatically collecting "big data" based on millions of online user play and socialization patterns in different CGVW like *World of Warcraft.* Similarly, studies reported in Hitomi (2010) evaluate the potential of CGVW for teaching STEM topics in primary and secondary education, where concerns for whether students will find CGVW-based simulations as credible as physical or video-recorded classroom science experiments (Francis and Couture 2002) are critical, as are whether students can transfer CGVW or simulation-based experiences to practical problem solving activities in the physical world (Fox, Kelly, *et al*. 2010).

Emerging Research Problems

Five different research problem categories have emerged through studies of CGVW in different SHEED application domains.

Developing and Using CGVW to Enable Computational Thinking

Scientific disciplines have well-established ways of framing and conceptualizing questions, devising methods, and formulating answers through established theories and frameworks. These can be expanded or conceptualized through "computational thinking," which allows a different way of dealing with the difficult questions of science. Computational thinking is a fundamental skill for everyone, not just for computer scientists (Wing 2006). It draws on the concepts fundamental to computer science to solve problems, design systems, and understand human behavior. It uses abstraction, modeling, and decomposition to tackle a large complex task or to design a large complex system. A key differentiating aspect of computational thinking from domain-specific approaches is its emphasis on representing questions and modeling problems at different levels of abstraction to allow distributed problem-solving. Computation, in this sense, is thought of as the process of making explicit information that was implicit (Kirsh 1992). In a study of algebraic problem-solving by students, the *Equations* (2010) game presented equations as constraint satisfaction problems, providing a better grasp of the process. This can be done in at least two different manners -- through procedural rhetoric of gameplay, and through game design and domain analysis.

Mastering SHEED problem domains through affordances supported with CGVWs

CGVW can further enhance mastery of research, development, education, and more in different SHEED problem domains. CGVWs offer the potential for new modes of inquiry and experimentation through visually rich models and behaviorally rich simulations of interrelated objects (Bainbridge 2007). Recent studies, such as those found in Bainbridge (2010), as well as emerging ventures commercializing emerging CGVW technologies, reveal a diverse a growing set of socio-technical affordances (i.e., new ways and means of collaborative work at a distance) are both supported and being used in practices including:

- *Group presentation, communication, conferencing, and social interaction* – virtual meetings of many different kinds that incorporate a sense of place at a distance, along with relevant work media (interactive reports, documents, presentations, 3D models, etc. -- many examples in Second Life), often as an alternative to currently available solutions provided by WebEx, GotoMeeting, and Skype-based online meetings.

- *Prototyping and review* – interactive design, construction, and modification of virtual objects, composite systems, or mirror worlds as potential enterprise products or services that can be used in proposals or design presentations (e.g., see Lopes (2009), along with Encitra.com at http://www.youtube.com/watch?v=M4cYiHZqN90).

- *Training, education, rehearsal, learning* – providing VW-based simulators where people can enact simple/complex behaviors to understand how best to use/service a simulated device (e.g., see projects the Discovery Science Center and Intel (Scacchi 2010a), also see examples from the *Little Big Planet* 2 game portal).

- *New product demonstration* – virtual product showroom, often with modeled/simulated interactive controls for selecting or customizing product features/attributes, such as color, appearance, accessories, etc.(see EONReality.com for online case studies).

- *Identity role-playing, team building, and other social processes* – often training centered VW but focusing on role-play, especially with attention to workplace diversity issues (cf. FutureWork Institute for identity role play, IBM efforts on team building, such as found in Reeve and Read (2011)).

- *Multi-media storytelling and avatar control/choreography* – creating video-audio animations (recordings) or live virtual action (live broadcast) of VWs for the purpose of illuminating narratives, telling stories (Lowood and Nitsche 2011) provide many examples of machinima for such purposes.

- *Mirrored worlds and memorialization* – creating virtual worlds that seek to strongly represent, primarily through visual means, some aspect, venue, or enterprise facility also found in the physical world. One reason for this may be to recreate or commemorate places that no longer exist. Another reason may be to help new users more readily acclimate during their initial immigration from familiar physical worlds, to seemingly familiar virtual worlds, so as to enable follow-on activities like training or role-playing. VWs that mirror physical worlds may also include support for control devices that affect action in the corresponding physical world place, and vice-versa using augmented reality techniques.

- *Game development and/or modding* – software development kits or modding tools (Scacchi 2010b) specific to a game engine (CGVW run-time environment) that streamline CGVW development using engine-specific content development tools (e.g., *Unreal Development Kit* for the Unreal 3 engine from Epic Games), rather than general-purpose programming tools or interactive development environments (e.g., Microsoft's *Visual Studio*).

- *Socio-technical process discovery* – ethnographic, virtual ethnographic, and computational (text data mining) approaches to discovering socio-technical processes emerging within CGVW work or play activities.

- *Enabling human behavior transformation* – CGVW designed to enable reflection, modification, and evolution of human behavior through repeated system-based training or usage settings, most clearly observed in CGVW for improvement of human health, ability, recovery, and self-managed care.

- *Modeling, analyzing, and developing complex intellectual property regimes accommodating multiple heterogeneous IP licenses* – understanding how developer or user-create objects or multi-object compositions within CGVW can be manipulated, exported, or imported across system boundaries, potentially for monetary or other forms of capital gain.

Affordances such as these can all support new ways and means of conducting collaborative research, development, and education in the SHEED domains. Collectively, CGVW represent a new engine for innovation and advancement, as well as to the creation, sharing, and enactment of new kinds of scientific knowledge.

Crowdsourcing Collaborative CGVWs for SHEED Applications

Scientific knowledge is traditionally created within the confines of specific sites of knowledge production such as labs, libraries, clinics, and so on. While effective and reliable, these sites are probably not the most efficient ways of knowledge production, nor are they sustainable in the future. The growth of science, the cost and expansion of requisite infrastructure, and the complexity of the questions faced in most SHEED-related areas (e.g., healthcare and environment) call for expanded methods and sites of knowledge production in science. This is already evident in the drastic growth of large collaboratories in certain areas of physics, biology, and elsewhere. The participatory and crowdsourcing approach of other areas of human activity such as software development, encyclopedic work, and journalism point to new possibilities. This approach can be creatively adopted in science in collaborative projects for modeling and simulation, which would involve learners as producers, and not just consumers, of knowledge. For instance, the Visible Human project provides a unique opportunity for education in human biology and physiology (NLM 2011). It also ties in with the emerging trend in healthcare IT where, for instance, the notion of a “virtual patient model” is envisioned as a central component of healthcare in the 21st century (Stead & Lin 2009: p.10).

Let us consider the new challenge of Reanimating the Visible Human*.* Such a challenge may entail a community-oriented open source computational modeling and simulation of the biological processes associated with a given anatomical system (endocrine system, cardio-vascular system, etc.) so that collectively the interaction of the systems computationally brings the Virtual Human to a multi-system simulation of a living being, this is a daunting research challenge. But if a large community of researchers and students can select a given anatomical system, element, or sub-component (down to the cellular or biochemical levels), then this community would progressively be able to develop their open source Virtual Human component modules as embeddable mini-CGVWs. These in turn could then be configured and composed into the overall architecture of the Virtual Human CGVW. Thus, how to design a Virtual Human that could collectively be reanimated through a crowdsourced approach to embeddable CGVW development represents a grand challenge for CGVW SHEED research that has a plausible path towards solution. Such a solution would itself represent a breakthrough in the research and education of the biological and medical sciences. Subsequently, our expectation is that there may also exist similar challenge problems in other SHEED research and educational domains that are amenable to crowdsourcing approaches to design, composition, and integration of embeddable CGVW-based models and simulations. Finally, the ultimate goal of achieving a reanimated Virtual Human and similar reference system models is that they can then become a new research platform, means of instrumentation, and media for education, dissemination, and publications of research results within SHEED problem domains.

Meta-Game Making Tools, Techniques, and Concepts

In order to involve learners and users in the process of knowledge creation, we need to provide them with tools and techniques that would facilitate their participation. One feasible approach would be the development of a game-making platform that can be easily used by a non-expert. The platform should allow learners to generate games in the same fashion that a presentation software (e.g., PowerPoint) allows a user to create their own slide show. These tools and techniques would encourage and enable the two-way transfer of knowledge and experience between SHEED domains and CGVW. In so doing, they would also create synergies between various academic domains—a critical necessity of scientific progress in our times.

One challenging area for new research focuses on the design and creation of a new generation of CGVW engines that embody complex processes and modeling structures that go beyond current physics, AI, and graphics engines. For example, at present, if biological or health science researchers want to create or reuse models of cellular biology or biochemistry to study the pathologies of new viruses, or the effects of new drug treatments, they either need to build a CGVW from scratch, or rely on current laboratory regimens that do not necessarily employ computational thinking, modeling, or simulation. Similarly, if biology or medical students need to study and learn such topics, they must do so in traditional ways--ways that ignore or miss the experience such students may already have from play, problem-solving, leveling up, and social interaction in modern CGVW. The widespread availability of biology engines at different levels of biological systems (from cellular to ecosystem) would open up new ways and means for advancing both research and education in biology, medicine, and health. Similar situations for research and education can also be seen in physical sciences including electro-magnetic physics, quantum physics, astrophysics, chemistry, energy production, environmental and earth systems science.

Challenges for developing CGVW engines supporting modeling and simulation of human and social sciences including psychology, sociology, and anthropology is also a tremendous opportunity area that lacks critical knowledge for how to design, implement, and refine such CGVW engines. Consider the case for ethnographic research and education in the social sciences. As noted, there are no CGVW engines for modeling and simulating ethnographic practices, nor ethnoscience processes. There is exciting new research on how to conduct ethnographic studies of social worlds within and around existing CGVWs, as well as a growing opus of published studies and results. However, there are not any reusable CGVWs available as infrastructure to support emerging research practices or educational experiences in the social sciences. Again, this is not a criticism of current research or educational regimens, but a recognition that engines that may enable new modes of research and discovery of new kinds of scientific knowledge, and new modes of education and training practices can follow from the invention, development, and (re)use of CGVW engines that support the human and social sciences.

Design of CGVW-based simulators and immersive environments for improving human performance or affecting transformative experiences

CGVW can be used within human-in-the-loop simulators or similar immersive environments. Such systems can enable physical, cognitive, emotional and others forms of affective experience that can improve human performance capabilities or transform human perception. Flight simulators are perhaps the most widely known of such systems. Dating back to pre-computing days, flight simulators were demonstrated as highly effective and low cost ways to train would-be (or experienced) pilots for how best to safely fly and operate an airplane under common, unusual or extreme flying conditions. In flight accident reconstruction, flight simulators are employed to re-enact pilot/flight operations prior to the accident to better understand possible causal factors, and to identify how to modify new training scenarios to avoid or overcome the accident pre-conditions, such as those encountered by US Airways pilot Chesley ("Sully") Sullenberg in his heroic landing of a commercial airliner into the Hudson River, in New York in January 2009.

Additionally, there is growing appreciation and application of simulators for vehicle driving or operation, such a race car simulators (e.g., http://motorsportsimulators.com/, http://uk.i-way-world.com/ or http://www.cruden.com/) now employed by leading motorsports racing teams and motorsports enthusiasts. Similarly, there is great interest and R&D investment in creating practical simulators for military/defense training applications in areas including flying military aircraft, operating military vehicles, and command and control, as it increasingly appears that retail computer games provide more engagement and immersive experiences compared to current military training simulators (Jowitt 2011). In defense applications, training includes learning how to prepare and engage in combat operations (Hussain et al 2009), as well as collaborative problem solving (Maxwell et al 2011, Scacchi, Brown, Nies 2011). In both flight simulators and motorsports racing simulators, human performance improvement under stressful conditions is a common goal. For example, in motorsports, learning how best to drive a race car more effectively can produce quicker lap times under different driving/racing conditions.

VW-based systems are also being applied experimentally and therapeutically to help *de-stress* combat soldiers suffering from Post-Traumatic Stress Disorder (PTSD) arising from the horrendous experience of warfighting and hostile-fire combat (Rizzo, *et al* 2009a,b). This kind of therapeutic intervention exemplifies how human emotional experience or perception of extreme fear, anxiety, or depression may be transformed or reduced to non-clinical levels. CGVW-based environments can thus serve an important role in enabling new kinds of therapeutic and rehabilitation regimens. What emerges as key research problems going forward are determining what levels of physical, perceptual or emotional realism (i.e., *verisimilitude*) must be achieved to enable change in human performance or ability. Complementary to this is determining at what order of magnitude cost (e.g., hundreds of dollars per user versus hundreds of thousands of dollars per user) must be invested in providing a research or therapeutic infrastructure that can achieve a sufficient level of realism or immersion necessary to enable behavioral change or transformation. As has already been demonstrated by flight and racing simulators, low-cost systems costing on the order of hundreds of dollars can be had for individual consumer usage, while professional or research grade systems that offer more immersive experience cost 10X, 100X, 1000X, 10,000X or more. But it is unclear what trade-offs arise and how much immersion or perceptual realism is needed (or can be achieved) to enable human performance improvement or behavioral transformation in different SHEED application domains.

In light of the above, we see the following as examples of key questions for research in the application of CGVW in SHEED:

- how to best create procedural SHEED content modeling and generation;
- how to streamline the production and evolution of SHEED CGVWs;
- how to generate design patterns and ontologies for creating visual metaphors that can be used effectively to translate SHEED domain concepts into game play mechanics;
- how to develop training engines and meta game environments for creating training games;
- what level of investment in simulator or wide-area simulation infrastructure is needed to achieve what level of immersion and verisimilitude that can enable human cognitive/physiological improvement or behavioral transformation in different SHEED application domains.

Future research infrastructure requirements

One of the key factors dampening further use of CGVW technologies within the SHEED areas is the cost of creating the virtual worlds in which training, simulation, or gameplay take place. Due to the relative homogeneity of the domain of computer games and virtual worlds, it is possible to make investments in infrastructure to create tools that are then subsequently adopted and used by large user communities. There are multiple examples of successful creation and adoption of 3D game engines (e.g., the open source *Delta3D* game engine (Darken, *et al* 2005) created at the Naval Postgraduate School) and physics engines for traditional entertainment-oriented computer games. These technologies have also seen widespread use in the more typical training and simulation applications found in SHEED domains. While game engines and physics engines have been a broad success, these tools still require game and virtual world developers to perform substantial work. There is a need to develop tools that can bridge the gap between the needs of CGVW developers in SHEED domains and the capabilities of current technologies.

Both the behavioral and visual elements of CGVWs are expensive to create, and hence there are opportunities for creating reusable infrastructure to reduce the cost and time required to implement advanced behaviors and create realistic, compelling visual elements for CGVWs. It is important to note that development of this infrastructure is not just an exercise in software engineering; success in each of the following areas requires the solution of multiple challenging research questions.

Reusable Domain-Specific CGVW Simulation Engines

Many current computer games take place inside virtual worlds where the physical interactions between objects are modeled realistically, using physical laws of motion. The underlying technology that makes this possible is called a Physics Engine, which performs a simulation of the physical elements found in a virtual world. Even though the underlying physical laws used to create the engine are well known, it is still very challenging to create a physics engine, due to the need for real-time speed of the simulation, the limitations of floating point numerical calculations, challenges in general-purpose 3D collision detection, and the need to provide interfaces that are compatible with existing game engines (Eberly 2003, 2006, Gregory 2009).

The physics of motion, while very important, is just one of many aspects of the physical world that might require simulation within a CGVW developed within the SHEED domain. We envision multiple research projects to develop simulation engines for multiple areas of science. For example:

- *Electromagnetism engine.* Current physics engines only model the physics of motion and kinematics. An electromagnetism engine would model electricity, magnetic interactions, electromagnetic radiation in an environment, and other electrodynamic activities in real-time, in a way that is compatible and complementary with existing game engines. As with other domains, an important issue is determining the correct level of modeling abstraction; many existing electromagnetism modeling environments are created for specific design problems such as antenna design (e.g., *PUMA-EM* project, http://puma-em.sourceforge.net/). It may be that in certain SHEED CGVW applications the right level is that of modeling electrical circuits, rather than low-level EM behavior. One can imagine both EM engines and circuit analysis engines designed for use in a CGVW, or other electrical components from the physical (electron) level, through (semi)conductors. An EM physics engine might then be extended to address other forces associated with strong interaction, weak interaction, nanosystem or molecular electrodynamics (e.g., van der Waal forces), or gravitation in ways that can be visualized and animated across a wide range of power scales (Fu and Hanson 2007).

- *Chemistry engine*. A real-time simulation engine that would allow mixing of chemicals in liquid and solid forms and provide a realistic simulation of physical, organic, or inorganic chemistry. An important challenge is finding the best approach for modeling chemical interactions. This could take the form of a large database of chemicals and their interaction properties, or a modeling approach based on more basic physical principles (e.g., a molecular modeling approach, such as is found in *Ghemical* (http://www.bioinformatics.org/ghemical/ghemical/index.html)). Ensuring the chemistry engine works in real-time and can interface with a game engine is another important constraint that differentiates this work from other existing chemical simulators. A chemistry engine should be consistent with the basis of a physics engine (e.g., so chemical reactions follow physical electrodynamic principles and atomic interaction patterns), as well as serve as a basis for a *biology engine* to provide both a chemical basis and physical basis for biological processes at the molecular level, since such bases are often misunderstood in practice (Hartley, Wilke, *et al*. 2011).

- *Ecosystem engine.* A simulation engine for one or more aspects of how a diverse ecosystem works. Elements of ecological systems that could be modeled include predator/prey relationships, broad movement patterns (e.g., fixed in place like a plant, slow ground movement like a snail, fast running like a cheetah), pack vs. individual movement, behavior over a day/night cycle, typical habitats, and so on, drawing upon the deep research literature on ecosystem modeling. Important issues include the level of modeling abstraction and span of modeled ecosystems: this could range from the microscopic to the macroscopic, from a backyard to a wide-range biological ecosystem. It seems likely that multiple ecology engines will exist, having made different commitments in their modeling approach. As with other engine types, we envision the constraints for real-time modeling and ability to interact with a game engine will be important elements differentiating this work from existing ecology models (such as, the *Terrestrial Ecosystem Model*, http://www.eos-ids.sr.unh.edu/tem.html). Additionally, as ecosystems can also be employed as an organizing construct for modeling and simulating technological ecosystems, then this engine could be generalized to accommodate different types of ecosystems.

- *Social systems engine*. A computational environment where diverse groups, organizations, or populations of virtual humans (or other organisms that naturally exhibit social behaviors) act to realize individual or shared goals through emerging trajectories of interaction and resource exchange. Computational modeling, generation, and visualization of city-scapes based on physical or synthetic cities are currently existing technical capabilities, but not so the people, communities, and enterprises that arise and socially animate such cities. Multi-agent simulations that form complex systems are also available to study selected behavioral dynamics, though lacking in rich individual actions that may be steep in historical circumstances, conflicting incentives for action, and other situational contingencies. So there is need for a new generation of CGVW that can be driven by empirical, hypothetical, or synthetic models of human or urban systems that can simulate the social, political, economic, and historical dynamics. Finally, it may also be productive to explore ways and means for integrating this engine with that for ecosystems, so that it becomes possible to realize and engine for modeling and simulating *socio-technical ecosystems*.

Many other examples of simulation engines are possible in both the physical sciences (astrophysics, climate, aerodynamics, etc.) and the social sciences (large scale social interactions, modeling specific sociological situations or urban dynamics, etc.) We note that each of the domains mentioned so far has a large existing community of researchers working to develop computational models of the domain. An ideal team developing one of these domain-specific simulation engines would involve computer scientists who understand the behavior of game engines working together with modeling experts from a specific domain.

As an example of how these simulation engines could work together to create a sophisticated simulation in the SHEED domain, consider the challenges inherent in developing a collapsed structure rescue training simulator. In such a simulator, a player would be responsible for navigating through a building that has collapsed after a natural disaster or human attack. Real world collapsed structure rescue is very dangerous, because of the potential for the building further settling, gas explosions or poisoning, and electrocution. A realistic model of a collapsed building should include multiple interacting simulation engines, including an electromagnetism engine to model the electrical circuits in the building, a chemistry engine to model gas flows and their interactions with ignition sources, and a physical model of the behavior of the structure. This example points to the need for additional research on middleware components that would mediate interactions among multiple simulation engines. Such a middleware could use a simple form of a concept net to reason that exposed wires with electric charge (from the electromagnetism engine) have the potential for creating a spark, which could trigger a chemical reaction (modeled in the chemistry engine) whose energy release in a small space could impact the structure of a building (in the structure simulation engine).

Future Proofing Future Assets

Historically, computer games have had a short useful lifespan. Any given computer game will seem current for a period of just a few years, and then be viewed as increasingly dated. Computer graphics are a large element of this process of obsolescence, with rapid advances in graphics capabilities leading to easily noticeable differences in the visual qualities of games over a period of a few years. Events such as the emergence of a new generation of computer game console (e.g., XBox to XBox 360, PS2 to PS3) can lead to even more rapid obsolescence. A major consequence of this is to drive up the costs for CGVWs. Any given CGVW will have a limited lifespan before needing a refresh of its graphics, thus limiting the span of time over which a CGVW can recoup the initial costs of development, and requiring periodic infusions of money to cover graphics upgrade costs. At least in the realm of educational games, what is more typical is a lack of investment in upgrading the graphics of a game, or porting it to more recent operating systems and consoles. As a result, many excellent educational games are no longer playable on current hardware and seem dated, despite the underlying educational approach being sound.

Another cost driver for developing compelling 3D virtual worlds is the need for an artist to develop 3D models of every object that exists in the world, all in a consistent visual style. In existing game studios, there can often be as many artists as developers working on a game title. In many SHEED CGVW applications, there are similar needs for 3D visual content. Buildings, cars, trucks, trains, military equipment, street signs, landscape items (trees, bushes), shipping containers, etc. are examples of visual assets that are commonly found in CGVW applications. At present, due to the lack of widely adopted interchange formats for both 3D models and animation characteristics combined with uneven support for existing standards in game engines, each project typically must re-create its 3D visual assets from scratch, at tremendous cost and duplication of effort.

It is an important infrastructural research challenge to develop 3D art assets that are at least partially future-proof. That is, we seek techniques for creating 3D art assets such that their underlying representation holds sufficient information to permit adaptation to improved graphics capabilities in the future. During use, such art assets would go through a process of adaptation whereby the available information would be tailored to the limitations of the existing graphics environment, and would be able to adjust its representation and animation based on the number of other 3D objects in a scene.

Key research questions in achieving this vision include:

- how best to develop algorithms for automatically reducing the number of polygons and the complexity of animation rigs based on the current graphics environment;
- how best to develop software plug-in architectures for representing common types of objects so, for example, when an improved skin rendering algorithm becomes available it can be added to an existing model;
- how best to develop procedural techniques for generating 3D models; and

- how to connect and interactively control the computational behavior of 3D models within domain simulation engines described above.

Tools for easy, rapid development of CGVWs in SHEED domains

Computer games typically can be characterized as falling within a specific game genre, with examples of genres including real-time strategy, action-adventure, role-playing games, etc. While all 3D games share certain architectural needs that can be met by existing 3D game engines, it is also the case that games within a specific genre have common genre-specific needs. A computer role-playing game, for example, typically requires a turn-based combat system, a character dialog system, and a quest system while, in contrast, a real-time strategy game requires none of these. It seems quite likely that CGVW applications in SHEED domains will also cluster into recognizable application genres, with similar opportunities for the creation of reusable infrastructures. As an example, consider the successful simulation game SimCity, which puts the player in the role of a city mayor who gets to control how a city develops over time. This game was successful as an entertainment product, but also has the quality that many instructors wanted to take the game and specialize it for their particular learning needs. If SimCity had been available with an easily extensible architecture, it is easy to imagine it being used as the basis for a series of city planning simulation games for various cultures and historical periods. Abstracting this idea, we can envision the development of game engines tailored to specific SHEED CGVW application genres in much the same way there are game engines developed for specific existing computer game genres. These game engines would be specialized for the specific simulation and interaction needs of a given SHEED application area, and via this highly tailored support, make it possible to quickly generate a family of similar CGVW applications. Such SHEED specific game engines are starting to appear in some domains. For example, the *TruSim* platform developed by Blitz Games can be viewed as a kind of domain specific game engine for creating healthcare training games (http://www.trusim.com/). The TruSim environment has been used to develop Triage Trainer, a game for training first responder medical personnel in how to triage injuries in disaster scenarios for most effective medical treatment, as well as the Interactive Trauma Trainer for learning how to manage trauma patients in conflict zones.

There are several existing game creation tools whose goal is to help people with low levels of computational skills develop working computer games. Among these, the Game Maker program is notable for its graphical programming language, and its ability to allow even very young people to create computer games (http://www.yoyogames.com/make). Unfortunately, Game Maker is not well suited for creating CGVW applications in the SHEED domain. Most SHEED CGVWs have one or more simulations at their core, with much interaction in the virtual world centered around manipulation of elements of the model. The core problem is that Game Maker does not have a built-in notion of simulation connected to the virtual world. We envision the development of game creation tools for applications in the SHEED domains, aimed at a broad game creating audience with low levels of computational skills. Such tools would make simulation models a first-class element of the game creation toolbox, thereby allowing aspects of the simulation to be worked into the game design.

Overall, we see multiple infrastructure research challenges to develop game creation tools, and game engines that make it substantially easier to develop SHEED CGVW applications. These tools and engines would be useful for a broad range of users, ranging from a broad population of game makers to professional game developers. The games created would similarly have a range of audiences, including K-12, college, and professional students, as well as a general population interested in learning more about SHEED subjects.

Broader impacts

Computer games and virtual worlds provide a powerful medium for transforming behavior and attitudes among players. Evidence indicates that CGVWs also promote computational and design thinking among those involved in the creation and development of these media. The benefits are thus manifold, impacting everyone involved in the creation, development, and dissemination of CGVWs. CGVWs also provide compelling online experiences for learning science and scientific reasoning (Aronowsky et al 2011, Honey and Hilton 2011, Metcalf et al 2011, Scacchi, Nideffer and Adams 2008, Steinkuehler 2008).

A 2008 Pew Research Center study found that minority students are adequately represented as players of video games (Lenhart *et. al*, 2008). This suggests that the transformational benefits from the use of CGVWs could apply to a broader audience. Within education, CGVWs can also potentially help address the under-representation of minorities in STEM disciplines in higher education.

Elsewhere, current investments in health/medicine have not led to a proportional reduction in health care costs nor to an increase in quality of life for the average American. CGVWs can lead to improvements in the quality of care and a reduction in health care costs. By promoting healthy behavior and enabling self-managed care in a fun, family-friendly manner, CGVWs can also lead to sustainable healthcare through education, training and transformation of lifestyles and attitudes.

Current investments in the SHEED domain may not lead as efficiently or effectively to socially valued outcomes. For example, advances in alternative energy and environmental science will not have the desired benefit without a corresponding change in the attitudes and lifestyles of consumers. Computer games designed using procedural rhetoric can help in transforming attitudes towards new research findings and demonstrate the benefits of these advances to players in a compelling fashion, thereby leading to changes in lifestyles. Additionally, through their use in education, CGVWs can help in increasing the scientific literacy of citizens. This can also lead to increased interest in STEM careers among players.

CGVWs provide an ideal platform for design, prototyping, and experimentation. The use of crowd-sourcing in CGVWs can promote collaborative approaches to conducting research. CGVWs in research can thus lead to qualitative leaps in new SHEED knowledge and transformational experiences.

Investments in research on CGVWs that become infrastructure can significantly reduce scientific research and technology development costs, while offering new ways and means for increasing productivity and reuse, as well as enable qualitative improvements in the fun and play of advanced SHEED research, education and practice.

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7. Discussion, Observations, and Recommendations

Walt Scacchi (Lead) and others.

The proceeding six chapters have identified and explored a wide variety of scientific, technological, educational, cultural, and practical implications arising from future research in computer games and virtual worlds. As noted at the beginning of this report, each chapter is a distinct product of its contributors, so each chapter can be read as self-contained, as they are not in a specific order of presentation, nor a linear narrative. Thus, the reader is encouraged to pay close attention to the chapters of most interest to them first, then to read across the other chapters to identify recurring research themes and problem domain characteristics. The online version of the report may be best suited for such readings (Scacchi 2012).

In this chapter, we briefly discuss some of the implications that follow, present observations that emerge through comparative readings across the chapters, and close with recommendations for further action that can put the embedded research agenda into motion by relevant government agencies, industrial centers, academia, and broader societal embracing of CGVWs.

Discussion

We begin by reviewing and recapitulating some of the highlights that emerged in each of the six chapters.

Computer Systems Research for CGVWs – transparent scalability up and down of processing and services appear as key elements of future IT infrastructure for CGVWs, from multi-/many-core processors, multi-blade servers, server clusters, and networked grids. This chapter focuses attention to outstanding research problems are found in identifying how best to design secure scalable CGVWs and federated CGVW software engineering mechanisms as advanced IT infrastructure that it can be employed transparently by game developers in the other SHEED, ABS, and MACH research application domains.

Advanced CGVW Technologies – generating playable games and rich explorable virtual worlds is a compelling and intrinsically motivating capability that many users desire. This chapter examines how best can model-driven and data-driven intelligent tools, techniques, and mechanisms be be designed and employed to facilitate automated or semi-automated generation of CGVWs for specific application domains.

Media, Art, Culture and History (MACH) of CGVWs – CGVWs represent both technology and media, and their embodiments need to be preserved in a replayable manner in the future. This chapters draws attention to creative CGVW meta-authoring tools and techniques that can also preserve and replay production of CGVW-based cinematic machinima to best support the documentation, reenactment, and reconfiguration of play/exploration experiences in ways that maintain their provenance.

Anthropological, Behavioral, Sociological (ABS) Studies of CGVWs – CGVWs increasingly represent new venues for social interaction at many scales of experience or encounter. Robust ABS scientific research depend on a ethnographically rich research infrastructure, research methods, and appropriate instrumentation needed to best capture, code, comparatively analyze, and describe emerging cultural and sociability practices, and how they emerge, are mobilized and deployed in order to serve diverse communities of interest.

Education and Learning with CGVWs – new generations of commercially developed CGVW may be repurposed to support new formal and informal educational and learning initiatives targeted to students (and teachers) in the K-12 grades. This chapter addresses how custom-build CGVW-based educational applications are designed to facilitate or explore new learning modalities and transferable experiences. It also raises questions for what kinds of techniques, tools, or frameworks are needed to best facilitate the automated development or repurposing of CGVW for different kinds of educational and learning experiences.

CGVWs for Science, Health, Environment, Energy, and Defense (SHEED) – development and application of CGVWs for different kinds of research domains are becoming evermore apparent, and represent a new way to advance and transform research and teaching practices in different scientific domains. This chapter explores the potential of new CGVWs to support the pursuit of research and application development in many high risk, high value application areas, including 13-18+ grade higher education in the SHEED domains. It also examines questions like how crowdsourced efforts may be mobilized to create innovative SHEED applications. It poses new challenges like how could we re-animate an all digital, visible human with computational models of their open source, independently developed, interacting physiological systems, as well as to customize such virtual beings to replicate living or historic human beings.

Clearly, some of these chapters focus their attention to core information technologies, while others address the creative, cultural, and educational potentials and practices that emerge. All the chapters identify current findings and research results in their focal domains of study, future research problems and opportunities, future shared research infrastructure needs, and broader impacts that can be stimulated and mobilized through strategic investments in CGVW-focused research.

Observations

The observations that follow collectively advocate investment in future CGVW research. Their intent is to be bold and stimulating, rather than timid and unnecessarily reserved. The observations presented follow from multiple readings of the chapters of this report by scholars whose expertise cover MACH, ABS, SHEED, and K-12 education disciplines, along with the technical expertise arising from deep knowledge of the IT systems and generative tools needed to produce next-generation CGVWs. These observations do not appear in order of preference or significance. Together, they begin to coalesce into a new narrative for why investment in CGVW research represents a timely, strategic opportunity for research agencies and sponsors, as well as for researchers in closely aligned disciplines, to seize the moment.

CGVWs as new media and technologies of practice have the potential to pervade most, if not all, sectors of scientific research, technology development, educational and cultural practices in industry, academia, and government. CGVWs are not a “killer app,” but instead are more like a “killer socio-technical ecosystem,” a far more socially diverse, culturally rich, and technically strong system for economic growth and resource transactions that no single app can ever hope to attain. *CGVWs are likely the next Web*: a new layer of systems and applications that can cross social, organizational, institutional and technological boundaries, just like the World-Wide Web has done over the past 15 or so years. In so doing, existing relationships among legacy IT systems may be disintermediated or reconfigured, and a new generation of socio-technical systems and relationships can emerge to transform many (not all) systems, institutions, and broader cultural practices. This has been the history of the Web, and now it may become a new history for the next generation of networking information technology systems, applications, and play/work practices.

CGVWs are not about mere "gamification" by which we mean turning existing socio-technical systems into those where users simply earn virtual badges, points, or prizes for accomplished game play. Not that there is necessarily anything bad or evil about such gamification, just that the potential of CGVWs is not about the trivialization of complex systems or institutional practices into banal entertainment in order to enhance the compliance or facilitate the consumption patterns of students, adults and scientists. No, CGVWs are rich socio-technical systems. In CGVWs, careful study reveals that play and work are often indistinguishable, except for the contexts in which they occur. Sometimes, its rewarding to work hard at play and having fun, as well as playing at work (and school) as a creative, fun way to reinvent legacy systems and create new learning-at-work practices.

CGVWs are embracing the next-generation workforce of those who will seek to work in the various MACH, SHEED, ABS, and advanced IT disciplines, industries or government agencies. It is not much of a challenge to find people under 30 years of age who know a lot about some CGs or VWs. Market research figures from KZero (2012) suggest that at least one billion people world-wide are now playing and interacting through CGVWs. Most of these people are young, not yet of college age. It may thus be simple to see that the future workforce for an IT skilled society and economy will be one that is based in large part on the experiences of young people now acting in CGVWs. Investments in STEM education in particular do not yet address this, nor do current R&D investments in next-generation IT identify this situation (NITRD 2012).

The U.S. currently leads the global development of new CGVW-centered products and services. Such socio-economic condition and market leadership can be accelerated through investment in a new CGVW research agenda, such as that identified in this report. New firms and highly skilled jobs will emerge through such investments into CGVW research, as can new markets, just as has been the history of the Web. The Web gave rise to new U.S. companies like Google, Yahoo, Amazon, Ebay, Facebook, Twitter, and more that have achieved global market leadership positions, while simultaneously expanding and transforming the markets for the adaptive incumbent IT-centered firms like Microsoft, Apple, IBM, Oracle, Hewlett-Packard, Cisco, Electronic Arts, Activision-Blizzard and others. Similarly, these transformations led to the acquisition, merger, or collapse of legacy firms that were unable to embrace and exploit the opportunities afforded by the new IT applications, services, and infrastructure enabled by the Web.

Future research in CGVWs can be targeted to different research agencies and research programs that can maximize interests through targeted investments. Games for health care represents one such application domain for focused CGVW research. The U.S. and many other developed countries are experiencing the ongoing growth in chronic care ailments like obesity, diabetes, asthma, and others. Unfettered growth of these ailments will clearly drive up the cost of health care in unsustainable ways, whether paid for by the government or commercial insurers. These ailments will increasingly be cared for outside of health care facilities, and increasingly will be the responsibility of the person or family who has the ailment. Games for health may be able to provide a new way and means for facilitating self-managed chronic care ailments that can be personally rewarding as well as transformative—not in the sense of curing the ailment, but in the sense of making the ailment amenable to personal activity and self-care more manageable.

Research in CGVWs overlaps most areas of current interest that advance the overall science research agenda for networked information technology (NITRD 2012). Massively multi-user

CGVWs represent new venues for communication and social interaction that generate big data about social, behavioral, cultural, and technological practice, all data that characterize societal processes. The defense research community has realized this, and is making research investments to advance such study to meet its mission objectives. But such purposes do not necessarily embrace the broader interests of the creative, cultural practice, educational, or scientific research communities. Elsewhere, CGVWs represent socio-technical systems (or ecosystems) that depend on, and thus stimulate demand for, advance computing infrastructure on a national scale. CGVWs raise new issues and concerns for cybersecurity, such as virtual identity theft of online avatars, international money laundering via virtual currency manipulation and arbitrage, or highjacking of global-scale game-based virtual economies. Last, new research challenge problems like reanimating the visible human can generate new scientific knowledge from domains that link or converge across nanotechnology, biology, information technology, and cognitive science (NBIC) disciplines.

The industries currently vested in CGVWs as entertainment media are not leading the way in pushing the R&D horizons identified in this report. Without coordination of research investment, CGVW technology will emerge as disjoint, islands of automation that will become evermore complex and costly to integrate for mutual benefit. The incumbent IT and entertainment industries are better served through a fragmented market that enables customer lock-in to particular technologies or popular applications, or one that enables domination by firms able to realize monopolistic positions that stifle innovation through institutional standardization of proprietary products or services.

Recommendations

This report identified six related areas that would benefit from strategic or programmatic R&D investments. The national NITRD (2012) agenda and grand challenge problem domains are both amenable to be favorably advanced through investment in CGVW research. In particular, the NITRD Program puts forward recommendations for a “planning and coordination support request” whose structure provides a model for what, where, how, when, and why to invest in to strategically stimulate CGVW research (NITRD 2012, pp. 19-20):

- **Co-funding** testbeds, infrastructures, and advanced tools/instrumentation for experimentation with new CGVW technologies, applications, or practices at realistic scales;
- **Workshops** that mobilize and bring together researchers, program managers, and socio-economic leaders to further identify and unify emerging research problem areas/topics, such as those identified in this report;
- **Collaborative deployment** of new CGVW system infrastructures, development tools and techniques, cultural/institutional practices, and repositories/archives across MACH, ABS, and SHEED focused agencies, R&D programs, and academic disciplines;
- **Interagency cooperation** to focus research investment that avoids the fragmentation and incompatible “islands of automation” that might otherwise arise through inaction and reliance on the existing entertainment industry to identify and provide solutions to challenges in mission-oriented SHEED programs;

- **Technical standards** that can increase the likelihood of interoperable, scalable, secure, and scalable CGVW systems, applications, and research instrumentation infrastructures.
- **Testbeds** that enable the joint R&D experimentation, crowdsourcing, and decentralized study of CGVWs of different scales and applications that enable cooperative study and practice within MACH, ABS, and SHEED disciplines, across agency programs.
- **Science and Technology Steering Council** to provide oversight and coordination of CGVW research investments across agencies, as well as incorporating the industrial and educational sectors at all levels.

Conclusions

CGVWs have emerged as an engine of innovation within each of the six research topic areas identified in this report. If the purpose of careful and cautious investment of limited funds is to realize the greatest benefits to many diverse public and private interests, then CGVW merits serious attention, consideration and commitment of resources that can fuel this engine of innovation. Such engines of growth and prosperity are uncommon and often elusive. CGVWs represent a technological arena and global market where the U.S. maintains overall scientific, technological, creative, cultural, and educational leadership. But starve this engine of the resources it needs to run effectively and efficiently, and it will falter and stall, thus nullifying the strategic opportunity at hand. Keep this new engine of innovation well fueled and fund its improvement.

CGVWs are emerging as socio-technical ecosystems for addressing national problems in areas such as education, socio-economic development, health care, and scientific research. This statement is based not on speculation, but on diverse R&D results, projects, and expertise cited in this report and beyond (see Steinkuehler Squire 2011). CGVWs represent transformative technologies and socio-economic practices whose time is coming (e.g., Corliss 2011, Marsh 2011, Reeves and Read 2009, Thomas and Brown 2009), and whose opportunity to invest is near at hand. CGVWs are changing the ways and means for how we come to know the socio-technical systems and cultural practices that surround us, especially for the next-generation of citizens who will take over and remake these systems and practices in their own image (cf. Braithwaite 2011). This report and the dozens of CGVW scholars who contributed to it, represents a starting point for these transformations. We welcome your comments, suggestions, and invitations to debate, refine, and advance the six research areas put forward as compelling starting points for beginning strategically focused investments.

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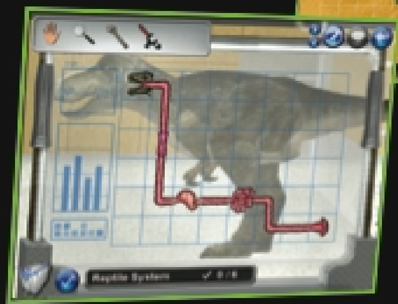
Reptile System


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