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Relational Experience Design for Immersive Narratives

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Media Arts and Technology

by

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ABSTRACT

Relational Experience Design for Immersive Narratives

Mengyu Chen

Immersive technologies are widely used in interactive media art and storytelling today. A high-quality virtual environment and avatar can provide the audience with a strong sense of presence and ownership of the virtual body, evoking empathetic outcomes from the experience. However, the majority of immersive art we encounter today shows a strong favoring of visual and auditory sensation over interactions. They provide the audience with a limited number of ways to participate in an immersive narrative, leaving them a sense of being an “outsider” that breaks the connection between the audience’s virtual avatar and the virtual environment. Starting with Nicolas Bourriaud’s relational aesthetics for art creation and taking human relations and their social context as the main conceptual and practical point of departure for experience design, I develop artistic and technical strategies for creating immersive experiences that place the audience at the center to let them activate the narrative content and cultural meanings. My approach is to provide the user novel ways to relate themselves to what they see on a screen, and to allow for direct participation and engagement. Through an increased level of interactivity, co-presence and plausibility in immersive environments, my work aims to help the audience develop new relationships with other people, with virtual entities, and with AI agents. The hybrid systems introduced in this thesis describe novel ways of creating relational experiences by techniques learned from different domains such as soft robotics, quantum computing and social science. I also demonstrate authoring interface design that can be more widely adopted by the creative community to overcome the challenges often faced in immersive and interactive narrative compositions.

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1. INTRODUCTION

Nicolas Bourriaud coined the term *Relational Aesthetics* in his 1997 essay collection in which he attempted to identify new trends in the practice of art during the 1990s. He proposed the possibility of relational art, a form of art that takes ‘the realm of human interactions and social contexts’ as its theoretical horizon [1]. His critical outlook aimed to resolve issues in art criticism left unresolved from the 1960s and 1970s, such as Arthur Danto’s “the end of art” theory [2] on the vanished boundary around the definition of art, and Theodore Adorno’s discourse about artwork as “the social antithesis of society” [3] on the growing “functionlessness” of art and its resistance against capitalist logic. Bourriaud, instead of trying to provide a new definition of art similar to what other theorists did, “chose to frame Relational Aesthetics as a theory of *form*. He advocated for a structure of art criticism that can reveal the characteristic features of the artwork. He wrote, “there is the possibility of an immediate discussion (at an art exhibition), in both senses of the term. I see and perceive, I comment, and I evolve in a unique space and time. Art is the place that produces a specific sociability.” Bourriaud then used a simple statement, “art is a state of encounter” to attribute the quality of art to human activities. This notion of encounter elaborated in his entire book laid out a theoretical foundation for emerging formats of art during his time, such as interactive software systems and participatory performance, both of which invite the audience to engage in the construction of meaning in the artworks.

In the 1970s, the domains of art, science, and technology started to cross over. With the rise of popular science, artists began a series of creative experiments and collaborations with partners outside of the domain of art, adopting new technologies and materials in their artistic expressions [4]. Software systems, kinetic sculptures, social practice, and many new forms of art boomed during this period and continue to influence each other as of today. While artists have never stopped pursuing new media and new technologies in their practice of art, formal discourses on such new expressions have been challenging. In today's art museum, experiencing an artwork sometimes invites the audience not just to view and walk around the art object, but also to touch, talk, engage, and participate. The emergence of using immersive technologies in the practice of art has further increased the difficulty for both critics and artists to discuss and talk about the artistic merits in the works. For critics, an immersive art experience not only has all the aspects of an algorithmic system, such as animated visuals, sounds, and embodied interactivity, but also often contains non-linear narrative components that may not have its full picture easily unveiled by only one trial of the experience. For artists, although new technologies in virtual and augmented reality have demonstrated full potential in rendering new realities and story worlds to their audience, the very limited theoretical and technical support to adopt immersive narrative as a major artistic medium has put constraints on artists' desires to build large-scale immersive artworks. Regardless, immersive storytelling as a form of art offers a tremendous opportunity for artists and can fundamentally change the way audiences perceive, experience, and think about the creative content and expression shared by artists.

1.1 Motivation

Contemporary art is often considered “esoteric”. The audience must have a critical eye in order to understand the artist’s intention and purpose behind an artistic expression. Intentionalist philosopher Paisley Livingston commented on the relationship between artist and artwork in his essay that “artists’ intentions have a decisive role in the creation of a work of art”, but these intentions “are not always successfully realized” [5]. Similarly, when art historian Arthur Danto encountered Andy Warhol’s Brillo Boxes that looked identical to the commercial product packaging, he saw all relevant purposes by the artist as “indiscernible” for those who are not insiders of art. Danto, therefore, declared “the end of the art”, a total liberation of art from “the need to understand itself philosophically” [2]. The definition of art, since then, has branched into many different directions, toward whatever ends determined by artists and their patrons.

This liberation of art has brought on a vivid contemporary art market since 1960s [6]. Pop art, conceptual art, and minimalism art started to occupy a large portion of the market, even though the truth content (conceptual motivations, personal meanings, etc.) of such works often remain obscure and inaccessible to the general public audience [7]. The downside of this freedom, in Danto’s words, is that “works of art do not wear their meanings on their faces.” However, this freedom has had a huge influence on the new generation of artists and art institutes. With a lack of consistency between the content and the means of presentation, artists no longer hold total responsibility for interpretation of the meaning of an artwork. Curators, directors of institutes, or even donors often step in to promote the artworks with contents that fit the best with their interests. Art critic Hal Foster warned about this influence on the production of art in the 1990s that, “the institution may displace the work that it otherwise advances: the show becomes the spectacle where cultural capital collects" [8]. When artists are deprived of control over the meaning of their works, they become merely producers of forms, of fashionable artistic commodities. They lose the audience who can truly listen to their feelings and stories. In other words, the narratives in art, if dominated by the institutions and capitals, can easily become an "assertion of private symbolic space of individual consumption" [9], as indicated by British art historian Claire Bishop.

As a practitioner of art for many years, I sometimes do see how institutions overshadow individual creativity. Artists, unless established, are often at a disadvantage during their negotiation with galleries and show venues about the presentation formats for their works. The contents of art can be easily compromised when its form has to be altered for the show. Nevertheless, I also see that artists have never stopped inventing new ways to overcome the challenges they face in protecting and promoting the fragile artistic narratives in their works. Some artists create interactive artworks with an aim to collaboratively elaborate the meaning of the work with audience input, while others design participatory forms of art to let the general public be part of the art presentation, offering the audience an opportunity to engage deeply with the work. Art critic and curator Nicolas Bourriaud coined the term "Relational Aesthetics" to describe such attempts and practices of art which gained popularity in the 90s as "a game being forever re-enacted, in relation to its function, to the players and the system which they construct and criticize" [1]. Artists design and create an artistic game, and invite whomever would like to participate and play it. Institutions, museum visitors, and the general public can all become its players, collectively holding responsibility for elaborating the meaning of the art.

My motivation for this dissertation is to expand the possibility of the forms of this relational game and to help artists gain more control over the narrative they can express through their art. While Bourriaud argues for a relational art form as an “inter-human game” that challenges the audience’s perception and understanding about the artwork and about the space where art is situated, I propose a broader and more inclusive model which incorporates non-human players and non-physical space in a mixed-reality immersive environment. Through the design of virtual experiences that blend with the audience’s physical context, I argue that adding different types of interactive relationships, that are directly or indirectly dependent on audience behaviors, into an art experience can greatly raise the ceiling of artistic expression, leading to more diverse and dynamic narratives revealed to the audience.

Immersive environments often include many types of virtual agents, such as humanoid characters, objects in motion, and landscapes. Most existing immersive art experiences are visual spectacles or walking simulators, where audience behaviors do not have much impact on these agents or the storylines formulated by their behaviors. In my work, I aim to transform the role of the audience from an observer to a participant, offering opportunities to construct unique audience-centered relationships based on interactions with various virtual agents. Through an augmented engagement with the artwork in mixed reality, I invite my audience to participate in an “inter-object game”, a situational experience where their individual choices matter and can lead to personalized narrative outcomes that are unpredictable but plausible.

Inspired by both scientific discoveries and philosophical thoughts, my exploration of the virtual aspects of an experience goes beyond common notions of physicality. Causality can be challenged and replaced by a quantum-like entanglement effect, and relationships can surpass the spatial and temporal limits in a virtual space to manifest the interdependency between objects. The goal of this rule-breaking method is to extend the possible ways of artistic expressions, by introducing new behaviors of objects and their connectivity with each other. Philosopher Karen Barad once said, “representations are not (more or less faithful) pictures of what is, but productive evocations, provocations, and generative material articulations or recon-figurings of what is and what is possible [10].” The potential of virtuality has given artists a new space of possibility to determine how objects can relate to other objects or people and manifest themselves. Every perceptual quality of a virtual object, either visual or auditory, can be seen as an inherent activity by the object that relates to its surrounding audience who can be affected. This activity does not have to be constantly static in the way we often encounter in real-life, but can be a dynamic and changing phenomena. Under this perspective, representation itself no longer only holds a perceptual form, but also an interactive one. Realism of a virtual environment can also be about a realistic manifestation of interactive relationships, describing unpredictable real life-like complex scenarios, which is the main theme I am highly interested in discovering in my works of art — to replicate or to simulate a new socio-ecological dynamism with real world reference in a virtual environment.

1.2 Building a Relational Reality

While artists have been creating immersive mixed reality art since the 1990s, the majority of immersive works we encounter today show a strong favoring of visual and auditory perception over interactions. Under the influence of a long tradition of artistic expression through drawings, sculptures, sounds, and videos, many artists chose to depict immersive virtual environments by using familiar despite new tools such as Tilt Brush and Adobe Medium. Immersive media, to some extent, can be said to be an alternative canvas for spatialized visuals and a different perceptual quality than traditional media, allowing for placement of digitally sculpted objects with spatialized sound that can help the audience engage in a multisensory experience. Creating a virtual reality under this premise is more about creating an immersive visual scene of animated graphics to let the audience experience the narrative through the visual design of a virtual space. The revelation of artistic narrative in such immersive works comes from the visual and perceptual aspect of the experience, in a manner similar to traditional media.

Although interactivity can be possibly added to expand the narrative space in an immersive artwork, it is often less prominent in existing works in providing meaningful narratives to the audience beyond letting the audience walk around the space or elevating their sense of embodiment with some playful effects. Part of this lower presence or preferred simplicity of interaction in immersive narrative expression is because of the fact that interactive effects between different virtual objects are hard to design and fulfill. It requires a high level of abstraction to describe the causal relationships between object behaviors and technical ability to implement such behaviors via programming languages. Part of it is also due to the challenge in presenting mixed reality artworks as interactive installations in which active engagement by audience input requires non-standardized logistics (individual viewing, guardians, etc.) as well as the design of robust bug-free systems that won't break during the exhibition. Any of these can cost artists and curators extra time, labor and effort to learn and implement. That is not to say that interactivity is not desired by artists. In fact, the popularity of the Processing and Arduino microcontrollers which began in the 2010s clearly shows a strong interest by the creative community in integrating interactivity into their artistic practices, especially when the technical bar to entry is lowered [11]. In some sense, if designing interactivity for an immersive experience can be as quick and straightforward as drawing and sculpting, artists are likely to start creating their virtual environments with a vision of a “dynamic and interactable reality”.

Advancements in game engines and visual programming (VP) tools such as Unity and Touch Designer, have made it possible for non-technical creators to produce simple interactive immersive experiences with their “code-free” interfaces. However, the priority of the visual sense can still be observed while using these tools. Creating animated graphics and 3D scenes often does not require writing code but defining a logical sequence of interactive behaviors that take different user inputs (movement, voice cues, gestures, etc.) to drive custom behaviors of virtual objects or render new narrative elements will very likely need extended knowledge of programming. Other than the tool designers favoring the creation of visual content, the “code-free” workflow enabled by most visual interfaces is not truly able to liberate creators from the burdens of programming. A VP interface is often designed to provide a faster way of production via the use of visual elements such as nodes and graphs as opposed to an interface that abstracts all forms of logic creation possible with code. On the one hand, VP can promote learning and understanding of the underlying programming constructs for beginners to start with by the way how code blocks are represented [12]. On the other hand, VP cannot guarantee a lower technical bar for the users to create their own programs with zero knowledge of programming. The result of this conflicting nature of mainstream VP tools is that if one has a deeper understanding of programming languages such as if-else statements, loops, or basic knowledge of algorithm design, then one will easily be able to compose VP programs [13]. Conversely, if one does not have any background in a technical field such as mathematics or computer science, one will likely have a steep learning curve, despite the visual interface, to implement any algorithms. For most artists who come from a non-technical background, the effort to learn to “design and think like a programmer” still needs to be eased.

In this dissertation, I present three methods to enable non-technical creators to truly benefit from the visual ways of creating interactive mixed reality experiences. My goal of building new tools for artists is to encourage artists to create and think like an artist, without having excessive constraints on their creativity imposed by the tools. At the same time, my custom tools and interfaces also enable me as an artist to explore new possible forms of relationships in an immersive experience, adding a diversity of expression to my works of art. It is worth noting that my research works not only explore the territory of interactive art practice, but also try to extend beyond it into a relational domain which encompasses participation, transactivity, and sociability as proposed by Bourriaud [1]. The key difference between interactivity and relationality in my works is that interactions are events taking place between different entities with spatiotemporal constraints, while relations are interdependent potentialities of a group of agents that can be conceived and manipulated by the audience to produce unexpected interactions, that leave extra narrative space for the audience to speculate, explore and interpret. Phillips and Huntley commented on the importance of relations in storytelling, saying, “It is the relationship between object and observer that creates perspective, and in stories, perspective creates meaning [14].” Similarly, in an immersive experience where the audience may encounter many objects, a variety of relationships between them can lead to many perspectives, and therefore, present a wider and more dynamic space of meaning-making to the audience.

1.3 Thesis Aims

VR artist Lynette Wallworth once said, “the capacity to see the narrative in the moment and to help to elevate it into meaning is what an artist does [15].” My thesis aims to support this artistic goal of storytelling in immersive media by focusing on the relational and participatory aspects of an art experience. Taking a stance against the formalist tradition of art which deprioritizes meaning and content, I believe that the value of an artwork comes from the narratives and relationships enabled by the artist. Through a set of art projects and tool designs with a core theme of building relational realities, I demonstrate how interactive relationships unique to an immersive environment can offer more forms of narratives and therefore more meanings in an art experience, evoking audience empathy and reflections upon individual behaviors and interaction choices. The end result is a new authoring system that can enable anyone to create such immersive narratives, opening a new possible future of relational experience design.

Working at the intersection of art and HCI, I see a gap that needs addressing — the process of art making is often highly ephemeral and anecdotal with no clear pattern to effectively communicate its core purpose or values, while HCI research is more empirical and follows a scientific way of thinking and reasoning. Reconciling these two distinctive styles of practice may appear challenging, but I also see it as an opportunity to expand the two domains of research. Benjamin Bratton described an interesting relationship between design and software in his book *The Stack: On Software and Sovereignty* that, “while Virilio’s axiom holds, and the invention of any new kind of technology is also necessarily and simultaneously the invention of a new kind of accident, it is true that the opposite holds as well: the accident also produces a new technology [16].” New forms of art are often made possible by the invention of new technologies, but we may also use artistic experiments to influence and drive the design of new technologies. Certainly, it may suggest a more empirical method and process of creating a work of art to better demonstrate its value, and HCI research that can depart from more artistic goals and imaginations.

I divide my research into three aspects to help my exploration of the design of relational virtual experiences: 1) artistic concept, 2) new media practice, and 3) creativity support. For the conceptual aspect, I explore the theoretical possibility of the design of relational experience with a particular goal to extend relational aesthetics into the virtual interactive domain. For the practical new media aspect, I focus on the methods and processes of creating relational experiences and attempt to connect the design space of relational art with existing practice and techniques of media art, such as VR installations and immersive storytelling. For the creativity support aspect, I present my designs of creative authoring systems to support easy and fast creation of virtual environments where various types of relationships can be created, along with evaluations and insights into the artist tools I have built and evaluated. I am hopeful that all these three aspects of my work inspire artists, designers, and researchers in the creative community to design and share new forms of artistic and storytelling experiences with a focus on developing interactive relationships.

To summarize, the main research aims of this thesis are the following:

- Explore the meaning of virtual relations in an immersive and interactive narrative, taking inspiration from sociological, philosophical and scientific concepts (Chapter 3).
- Explore new methods to create an inclusive, collaborative and dynamic virtual environment as a new immersive art form where different virtual objects and elements

are influenced by each other resulting in various behaviors that are triggered by the presence and interactions initiated by the audience (Chapters 4 & 5).

- Explore the design space of virtual relations that can lead to emergent narratives, providing a personalized experience that is unpredictable and captivating for each user (Chapter 4).
- Use procedural and entangled relations to simulate the real-world complex cause-effect relations and entangled situations, creating fictional but plausible socio-ecological dynamism in virtual space (Chapter 5).
- Develop authoring systems that support artistic creation beyond the limit of current methodologies, freeing creators from coding (Chapters 5 & 6).
- Design tools for non-technical creators to create complex interactions and relational chained activities between virtual elements and audience in an immersive environment and help raise the ceiling of artistic expressions with low effort (Chapter 6).
- Evaluate the validity of the designed techniques and tools. (Chapter 6).

1.4 Dissertation Overview

This dissertation is centered around a series of conceptual explorations about virtual relations and the possible methods to design a relational experience in an immersive environment (Chapter 3). The thesis starts with a broad background discussion about relevant areas of research and critical theories combined with an introduction to several artists and their artworks that are representative of key artistic concepts in Chapter 2. A more in-depth conceptual investigation of specific design strategies and methods regarding virtual reality system design and storytelling is rendered in Chapter 3. By looking at inspirational works in philosophy and sociology, I discuss how those ideas can be translated into creative practice by a new relational ontology in virtual reality. Based upon the strategies proposed in Chapter 3, I then demonstrate the actual application of the key concepts in both relational experience and authoring tool designs.

Chapter 2 starts with a discourse on how relational aesthetics can be expanded into the virtual domain. I then introduce several important HCI concepts regarding immersive virtual environments and intelligent virtual agents, and how they have been previously associated with creative art composition. Besides that, as this thesis is built upon a highly multidisciplinary practice, I also give a brief sociological and philosophical background discussion on the key concepts such as actor-network theory, political ecology, and agential realism, all of which are useful to help the reader better understand the context of human and non-human interactions and relationships. A practical overview of interactive storytelling and AR/VR authoring tools are given at the end to provide a general sense of how we may improve and design a better virtual system.

Chapter 3 introduces a relational ontology in virtual reality. I discuss the advantage of a process-oriented relation composition method as well as the idea of a split reality that may help us keep good practice regarding our immersive experience design. This chapter ends with four principles that can be used to help future creators design and build a relational reality.

Chapter 4 presents two of my projects in designing relational immersion as artistic expressions. Biometric Visceral Interface shows a new hardware design that helps two remote participants establish an intimate relationship via haptic feedback. Eccentric Nature explores the design and creation of a new type of virtual relationship between human and non-human participants, suggesting the possibility of a virtual ecology where we may live equally with other virtual entities.

Chapter 5 presents two relational storytelling tools that can be used by non-technical creators to design and deliver relational storytelling experiences. SceneAR allows anyone to create, view, share and remix scene-based AR stories on a smartphone and lets them collaboratively make new stories together over a virtual social network. EntangleVR focuses on using the concept of quantum entanglement to let the users easily compose correlations between virtual objects and participant interactions by a visual programming interface.

Chapter 6 presents a comprehensive authoring method for relational experience design. ConnectVR provides a no-code workflow and visual interface to let creators easily design complex cause-effect relationships (e.g., butterfly effect [17], chained reaction) for more effective immersive storytelling. It also lets the creators design multimodal interactions with virtual characters and agents by voice and gesture so that the participants can be more engaged within the virtual world.

Chapter 7 presents a discussion and comparison between EntangleVR and ConnectVR to examine the results of both evaluations based on my relational experience design concepts. I also provide some reflection on relational aesthetics with respect to art-making and tool-making practice.

Chapter 8 concludes the dissertation with a summary of different relation creation techniques and concepts, as well as identifying potential directions for future work that are exciting to be explored.

1.5 Thesis Contributions

The goal of my work is to design meaningful relationships between human and non-human agents and construct a virtual ecological and social dynamism where narratives and meaning can emerge. I call my practice “relational experience design,” i.e., immersive experiences that invite the audience to participate and interact with the virtual environment, building new relationships with other humans, with the virtual space, and with AI agents in the virtual space. In such experiences, one simple interaction initiated by a user may have an extensive impact on others in the space, or even project a long-lasting butterfly effect similar to how cause-effect relationships may evolve in the real world.

Through user studies, my relational experience design has shown to, 1) provide novel ways to connect the audience and the virtual surroundings using diverse interactive techniques and devices, 2) raise the ceiling of artistic expression and interactive narrative design, and 3) open up new possibilities for participatory artwork in a virtual context.

As there are no common or standardized ways and tools for artists to design complex relationships in a virtual environment, I develop my own tools and interfaces to facilitate the creative process. I use my own artworks as initial attempts to explore possible ways of creating relational experiences, and then validate my ideas and hypothesis via different authoring systems and formal user studies so that my practice can also be learned and shared by the creative community. In this thesis, I have included two art experiments and three authoring systems that I made during my PhD to demonstrate the design space of relational experience, with a hope that they can provide both conceptual and technical guidance to fellow artists and researchers. I summarize my contributions in art and HCI as follows:

- A relationship-based framework that takes the audience as activators of an immersive art experience with their conscious and unconscious behaviors.
- Novel techniques for incorporating soft robotics and haptic feedback to build remote interpersonal relationships between human users.
- A new smartphone-based AR storytelling system that promotes collaborative relationships among non-artist users.
- A new design space of using the concept of quantum entanglement to create interdependent relationships in a virtual environment.
- Visual programming interfaces and pipelines that enable non-technical creators to build complex interactive relationships and chained reactions in a virtual environment.

2. BACKGROUND

This thesis builds on prior work in immersive experience design, human social interaction, computer simulation and AR/VR authoring tools. My research aims to introduce ways of creating a relational reality of interrelated objects, providing not just a visual and perceptual experience to the audience but also a large degree of interactivity that promotes participation, collaboration and social connection. The ideas presented in this thesis are informed by prior work in art, philosophy, sociology, quantum physics, and human-computer interaction. This chapter provides an overview of these areas and introduces how they influence my way of thinking about relationships in a virtual space as well as the challenges in enabling these relationships.

2.1 Relational Aesthetics

Nicolas Bourriaud published his *Relational Aesthetics* in 1997, a collection of essays in which he tries to find a new way to approach contemporary art practice during the 1990s. In Bourriaud's opinion, the emergence of new elements often observed in artworks under the influence of postmodernism, such as participation and sociability, no longer fits with precedent theories of art, making it difficult for artists and critics to discuss and identify the new tendencies in contemporary art [9]. Rejecting the popular formalist ideas of art as a self-contained object of pure perceptual values by critics such as Clement Greenberg and Roger

Fry, Bourriaud argues for the openness of art to the public and seeks to provide new criteria to approach the emerging art forms for their complex nature involving dynamic and interactive relationships with the environment and the audience. For instance, Bourriaud said:

> "Art has always been relational in varying degrees, i.e. a factor of sociability and a founding principle of dialogue. One of the virtual properties of the image is its power of *linkage*, to borrow Michel Maffesoli's term: flags, logos, icons, signs, all produce empathy and sharing, and all generate bond." [1]

The word *linkage* here comes from *reliance,* a French psychosociological concept with the meaning of "re-linking" or "re-binding", referring to the reconstruction of human and social bonds that have been more or less destroyed by modern societies [18]. To Bourriaud, art is particularly suitable for creating a linkage between people, as an artwork, especially a work of new media, is often made of various expressive cultural elements that can easily produce shared empathy and meaning. In other words, instead of investigating a traditional relationship between artwork and audience, Bourriaud's discourse on art is about how art is able to serve as a place to "produce a specific sociability" [1], and how it is to create a temporary community within an exhibition space for audiences of connected shared experiences.

Viewership under this new framework of linkage is no longer about individual perception or consumption, but about participation and connection through a collective experience that is contingent upon the environment, time, and dynamism. Bourriaud used the word "encounter" and "exchange" to describe a situation brought by contemporary artwork. Encounter implies an unexpected state of seeing, and exchange depicts an activity that goes beyond verbal or non-verbal communication, a more engaged form of involvement with potential gain and loss. In many relational artworks, this exchange nature is reflected as a responsibility or expectation to the audience to activate the content of the art. Artists such as Rirkrit Tiravanija, Thomas

Figure 1. Thomas Hirschhorn's Gramsci Monument (2013) at Forest Houses, Bronx, New York. The artist built a participatory housing structure dedicated to the Italian Philosopher Antonio Gramsci. The structure hosted a series of philosophy lectures, poetry readings, performances, and workshops for the public visitors from the neighborhood. Image credit: Wikipedia.

Hirschhorn, and Liam Gillick often create communal experiences where the audience is placed at the center of the art and needs to talk, read, cook or eat with the artist in order that the artistic meanings of the work can be rendered (see Figure 1). Without contributions from the audience, such works would be meaningless. For instance, Liam Gillick once said:

> "My work is like the light in the fridge, it only works when there are people there to open the fridge door. Without people, it's not art – it's something else – stuff in a room." [19]

At the same time, this requirement of participation also makes it possible for artists to collectively elaborate the meaning of artwork together with the audience. What is important about this possibility is that every participant in the space, as Claire Bishop indicated, is now a meaningful member instead of an anonymous individual being addressed as a collective whole [9]. Every single action brought by the audience can have an impact on the content of the art as well as transform the space containing the art object into an unexpected project site. In Bourriaud's relational aesthetics, every artwork is essentially a political project as it "tightens the space of relations", and relations create new meanings.

In addition to this shift from viewership to community membership, relational aesthetics proposes the idea that a work of art does not always need to be on display in a museum or gallery, but can be located in any space. As early as the 1970s, conceptual artist Joseph Beuys had developed his "social sculpture" practice to place an artwork in daily life, and claimed that "every man is an artist" [20]. His art experiments were often created in public spaces together with the local communities so that everyone can have the opportunity to become a creator, a sculptor, or an architect of the social organism. German artist and writer Hito Steyerl in her book *The Wretched of the Screen* similarly describes a historical transition of art's autonomy that happened during the 20th century from its intended separation from life to its dissolution within life for the purpose of evasion of instrumentalization [21]. Steyerl believes that, as a result of artists' constant refusal to follow the division of labor or the specialization required by other professions within the bourgeois capitalist system, artists frequently try to break the barriers of art and recreate its relation to life. It is worth noting that the open-endedness and the interactivity of a relational artwork happening outside of a commercial space do not exclude it from being an object of a commodity. Bourriaud originally expected that the relational form of art can fulfill a goal to serve as a "microtopian" area that is free from the normalized social economy and commodity production, he did not, however, predict the fast rise of the experience economy, a concept invented a year right after the publication of his works, overtaking the idea of participation and environmental connection into the domain of commodification [22]. In some sense, Bourriaud identified the huge value of participatory experience in the art world, without knowing that it would also be absorbed into the global economy soon in a year.

Nevertheless, the contribution of relational aesthetics to the contemporary art world has been far-reaching. It provided new ways to think of art with respect to not just the object of art itself, but the artistic and social context it creates. My research departs from a similar vision of meaning creation by relationship building but focuses more on its potential value in the design of an immersive art experience. Specifically, I propose several new additions to what may constitute a relational art experience: 1) a non-anthropocentric approach to think of and involve non-human agents and entities, 2) a participant network to incorporate a sequence of cause-effect and interdependent relationships, 3) inclusion of virtual environment as an additional layer on top of a physical environment to create a hybrid and mixed-reality space where a work of art can be situated. The expansion of the participant group and the spatiality allows more complex and dynamic relationships to take place, and therefore potentially letting the audience and the artist create more interesting narratives and meaning together. In the following chapters, I present my projects and art experiments that explore the design space of interactions with various virtual agents, characters, and remote users in augmented and virtual reality environments, attempting to deliver a new type of immersive narrative experience where the audience can fully engage and participate in a dynamism of complex relationships.

2.2 Immersive Virtual Environment

In 1994, Milgram et al. proposed the concept of Reality-Virtuality Continuum (see Figure 2) [23], placing physical reality and virtual reality (VR) at opposite ends of a continuum and

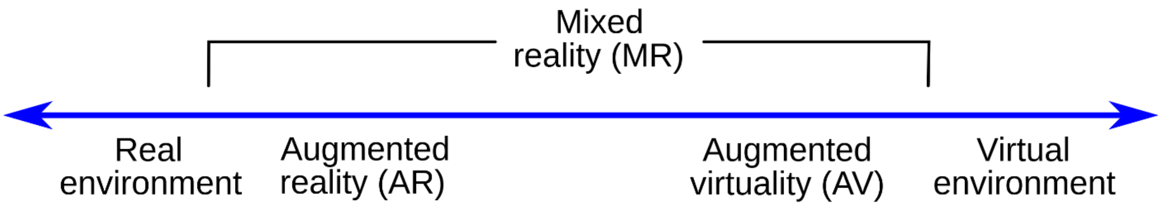


Figure 2. Reality–Virtuality Continuum is a continuous scale ranging between physical reality and virtual reality. It encompasses all possible variations for mixed reality.

augmented reality (AR) in between, to better classify the consistent relationships of these technological terms. A virtual environment, which is a synthetic world simulated by a computer, can be seen as an ideal extension beyond our real-world environment. It allows a participant to step out from their familiar physical surroundings to see and interact with a new environment that is either fictional or existing. A few years later, Mel Slater in 1997 proposed a framework for immersive virtual environments (IVE), in which he defined two important concepts – *immersion* and *presence* – to help produce better understanding of the psycho-physics, display systems and simulation factors associated with virtual reality experience design in the HCI context [24]. Immersion under this framework is described by the technical characteristics of a system, based on its capabilities to deliver "an inclusive, extensive, surrounding and vivid illusion of virtual environment to a participant." Presence refers to a state of consciousness of the participant and their illusion of being there, which is often mutually associated with immersion. Slater in 2009 described an additional concept, *plausibility illusion*, to describe the illusion that the scenario being depicted is actually occurring, even though the participant knows that it is not real [25]. The three concepts are well adopted by the community, and have led to many interesting discoveries and findings about unexpected behaviors of participants in virtual space regarding their virtual body ownership [26], social awareness [27], and performance [25], etc.

Artists’ expedition into the virtual territory has been cautious, critical, and full of cross-disciplinary debates since the 90s about its possible impact on different aspects of digital culture such as space, reality, community, social equality, and authenticity of the experience. In the eyes of artists, reality and virtuality may not be on a continuum about physicality or syntheticity. Virtuality exists more like a migration toward a new world order where humanity can be greatly empowered, although they may find that this migration isn’t happening as soon as what they expected if they were to see it today. Banff Center for Arts and Creativity since 1990 has started to invite artists and writers across the globe to explore the theme of art and virtual environment. The center in 1991 hosted its very first symposium following its artist residency program, the Virtual Seminar on the Bioapparatus, and brought together pioneer artists, philosophers, and software designers, such as Char Davies, George Legrady, and Jean-Francois Lyotard, to have formal discussions on the potential implication of virtual environments concerning art and humanity [28]. Mary Anne Moser, who later became the director of Banff Center, commented on this initial attempt in the art community as:

> “The Bioapparatus residency was significant in the way it highlighted the antinomy that characterized discourse around cyberspace. Proponents of virtual reality were zealous in their defense of no-holds-barred development, envisioning worlds full of possibility once human presence could be better controlled. Critics were equally vociferous: controlled by whom? Accountability for the impact of new technologies on power relations (and thus on social, cultural, and environmental conditions) was demanded.” [29]

Moser particularly used the word cyberspace as an alternative to virtual environments. She thinks that the incorporation of virtual reality in the practices of these artists was mainly rooted in two concepts: cybernetics and internet culture. For artists who work with virtual environments as an expressive medium, Cybernetics means a mapping of the entire human sensorium to a virtual environment, imitating and reproducing life forms in a virtual space.

Internet culture, on the other hand, has the potential to allow participants to be emancipated from physical bodies and materiality, and to dismantle the hierarchies of power and unequal social relations produced by racial or gender bias [30]. That is, it is more frequent to see that artists in the 1990s were interested in using the word "disembodiment" together with "embodiment" to talk about their art and virtual environments, not because of the lack of technical capacity to create an embodied experience, but because their ideas were sometimes to intentionally disconnect people from the physical reality, and reconstruct an alternate virtual counterpart elsewhere to serve as an ideal destination. For example, Diane Gromala's *Dancing with the Virtual Dervish: Virtual Bodies* (1994) actively explores the process of disembodiment as a transcendent and spiritual function of virtuality [31]. As a person with years of experience of chronic pain, Gromala's goal was to simply create the illusion of disembodiment and draw a sharp boundary between the body and the image on the screen. In this way, an alternative universe free from the pain of the physical body may be created. Lawrence Paul Yuxweluptun's *Inherent Rights, Vision Rights* (1992), the first VR artwork exhibited by the National Gallery of Canada, explores this idea of Native Modernalities by letting the audience walk into a virtual environment full of contradictory and conflicting elements with a sense of disembodied-embodiment. As Yuxweluptun's goal was to create a space of intersection and hybridization of Western and Indigenous technology and aesthetics, artist and writer Jackson 2bears described this work as an "ecstatic experience that confuses, discombobulates and dislocates the entire sense of 'self'" [32].

As a simulated virtual environment does not have to have real-world properties and can be flexible about its compliance with the laws of physics, it is particularly suitable for artists to create expressive artworks reflecting their imaginations or ideas that are hard to materialize. If we use an HCI lens to look at these works, we may surprisingly find that many of the artistic attempts can be said to cross over with the three aspects of IVE. For example, Char Davies' *Osmose* in 1995 explored the "perceptual interplay between self and world" [33] by inviting the audience into a virtual forest of trees, leaves, clearings, ponds, and mysterious codes and texts. The interactive system behind the work associates the audience's breath and proprioceptive modalities with the virtual environment to increase the level of immersion, which challenged conventional approaches to virtual reality at the time. Laurie Anderson and Hsin-Chien Huang's *Chalkroom* in 2017, which received the award for Best VR Experience at the Venice International Film Festival, invited the audience into a breathtaking VR environment of eight different architectures where they can levitate and float freely [34]. Instead of using highly realistic visuals to increase the sense of presence like many other VR experiences, the artists chose to use child-like and abstract chalk drawings along with compelling poetic narratives to link the participant's personal memory with Anderson's inner thoughts and experiences, invoking a strong place illusion not about physical space but about one's meditative inner mental world. Alejandro G. Iñárritu's *CARNE y ARENA (Virtually present, Physically invisible)* exhibited at LACMA in 2017 explores the human condition of immigrants and refugees and focuses on creating a strong plausibility illusion for the audience through highly realistic visual, auditory and haptic experience [35]. The audience needs to take off their shoes and walk with bare feet on dirt ground as if becoming a refugee crossing the US-Mexico border. Such an experience significantly increases the participant's presence in the virtual space and potentially makes it easier for them to believe that their direct encounter with the armed police force in virtual reality is truly happening.

Although the works by artists are not meant to advance the technologies related to the immersive virtual environment, these exploratory works are often good examples demonstrating some of the hypothetical ideas HCI researchers may have. In this thesis, I focus on constructing various relationships in a virtual environment to enhance the participant's plausibility illusion. Experimental artworks were also created as examples to validate my hypothesis about building an interactive system that can increase the level of presence for the audience.

2.3 Intelligent Virtual Agent

People's fantasies about intelligent agents can be dated back to the 1940s when the first computer was just invented. Right after its birth, Alan Turing quickly thought of its potential in replacing human intelligence and proposed his famous Turing Test to evaluate a machine's ability to exhibit behaviors that are indistinguishable from that of a human [36]. Computers can be said to be the first kind of intelligent agent that has been continuously developed and upgraded by human society. Scientists and researchers since then have sought to create robots or computer-generated characters as ideal companions, with the hope that one day they can bring those smart AI characters depicted in science fiction, such as Blade Runner and Star Trek, into our reality.

One of the earliest computer-generated agents, ELIZA, was created in 1966 by Joseph Weizenbaum at MIT as an experiment to create a conversation between humans and machines [37]. Although ELIZA did not even have a screen to display visual information and was only linked to a teletype device for one to communicate with, it was able to deliver a coherent conversation with the user and even made its user at a certain point believe that ELIZA was a real person [38]. Seeing this opportunity of creating virtual characters that can have persuasive behaviors to make people believe they are real humans, Joseph Bates in 1994 defined this concept of “believable agents” and specifically introduced the idea of *the illusion of life* in the design of these characters [39]. Bates’s research focused on using emotions to construct believable agents and aimed to build computational models that can represent the emotions on these characters. What’s interesting about Bates’s work is that he departed his investigation of believable agents from looking into how artists tried to portray characters in motion pictures as well as their understanding and expression of the essence of humanity in their works. He said:

> “It can be argued that while scientists may have more effectively recreated scientists, it is the artists who have come closest to understanding and perhaps capturing the essence of humanity that Beldsoe, and other AI researchers, ultimately seek. If this is true, then the results of artistic inquiry, especially the insights into character animation such as those expressed in the Illusion of Life (Thomas and Johnston, 1981) and elsewhere (Jones, 1989, Lasseter, 1987), may provide key information for building computational models of believable interactive characters.”

Bates specifically studied how Thomas and Johnston at Disney defined ways to capture and portray the emotional reactions of their animated characters. These findings were later translated by him and his student Bryan Loyall into the building of interactive agent behavior models that are based on personality, emotion, motivation, and social relations [40].

Although Bates’s believable agents laid out a foundation for this research domain of intelligent virtual agents, it was not until the early 2000s that more work started to be done about it. The technologies for building an intelligent virtual agent require expertise in many different areas such as computer graphics, voice synthesis, natural language processing, and behavior simulation, while early works mostly focused on only voice feedback to deliver social interaction, which lack the ability to provide non-verbal cues for a more believable experience.

In 2001, Justine Cassell introduced her work at the MIT media lab on building Embodied Conversational Agents (ECA) as an intelligent user interface to carry out face-to-face conversation-based tasks [41]. The work not only demonstrated the possibility of delivering a high-quality social interaction between humans and machines but also raised new questions about how one should design the interface for an intelligent system and represent information conveyed to human users by different modalities. The usage of intelligent virtual agents then started to be explored in many different scenarios such as literacy learning [42], computer-based learning [43], job coaching [44], clinical psychiatry [45], storytelling [46], etc. With further development in AR and VR technologies, it becomes possible that virtual agents can appear more real by various natural interactions with human users in a mixed-reality space. Daniel Wagner et al. presented a way to display virtual characters in an AR environment and explored how realistic the character needs to be for an effective and engaging educational experience [47]. Kim et al. studied the influence of visual embodiment and social behavior on the perception of intelligent virtual agents in AR and specifically showed that an agent with a visual body in AR and natural social behaviors can make the user more confident in believing the agent’s ability to adapt to and influence the real world [48]. Max is a believable agent created at PlayStation that is displayed on a holographic light field display and has the capability to interact with the user by voice, hand gesture, and face tracking as if it is in the real world. [49]

While computer scientists are trying to deliver interactive virtual agents of higher fidelity, artists have also been trying to incorporate them into their works of art. Their practices often start with their own visions about artificial intelligence as a broader conceptual point of departure exploring the intersection of technology, nature, and humanity. Lynn Hershman

Leeson's *Agent Ruby* (2002) was exhibited as an expanded cinema part of her sci-fi fantasy film *Teknolust* [50] that centers around the topic of gender issues, biotechnology, and the consciousness of AI. The audience can chat with Ruby via a web interface and Ruby, who has a female face, will respond to the typed input by searching for information from the internet to increase her body of knowledge. Leeson in 2004 upgraded Ruby into DiNA, a fully animated 3D agent with a realistic face, to provide the audience with a more natural way to communicate with the agent through face-to-face voice-based interaction. Lawrence Lek's CGI film AIDOL in 2019 showed a fantasy world staged in South-East Asia where superintelligent AI characters have developed their own jungle culture that simulates human civilization, such as music, e-sports, and architecture. Lek described this space of intelligent agents as a "post-AI world where originality is sometimes no more than an algorithmic trick and where machines have the capacity for love and suffering" [51]. Stephanie Dinkins in collaboration with Terasem Movement Foundation created a series of video art about the artist's conversation with BINA48, a realistic human-faced social robot that has its own thoughts and emotions [52]. The conversations were often about racism, gender issues, robot civil rights, love, and philosophy, and were displayed as a documentary series exploring a long-term relationship between humans and machines.

The idea of intelligent virtual agents in the context of artistic creation is often not limited to humanoids or human characters. Artist and software developer Karl Sims focused on designing and programming non-human creature-like agents that can evolve and adapt to their environments. His creatures were composed of virtual brains, effectors, and sensors to be able to dynamically adjust themselves while their morphologies and neural systems for muscle force control were generated by genetic algorithms [53]. In this way, the creatures displayed realistic locomotion behaviors. Similar but different from Karl Sims' work, Ian Cheng created an artificial lifeform, Bob, who takes the form of "a chimeric branching serpent" [54]. Driven by an AI algorithm that dynamically changes Bob's beliefs, behaviors, and emotions, Bob evolves and grows all the time during its exhibition in a gallery space. The audience can use a mobile phone app to feed different thoughts to Bob and influence its evolution. In this way, the final formation of this virtual creature is determined not just by the artist, but also by the audience.

Although there is a tremendous design space for intelligent virtual agents in the practice of art, due to the technical barrier that crosses over with many different domains, this area of agent-based art is underexplored. My works look at building new tools to lower this technical barrier and support artists to create intelligent virtual agents that can dynamically respond to human interactions, with an aim to enable more expressive storytelling in a virtual space.

2.4 Networked and Entangled Reality

To better extend relational aesthetics into the domain of virtual reality creation, we can use actor-network theory (ANT) as a methodological approach to describe the activities and relationships between human participants and non-human agents. In Bruno Latour's 1996 article *On actor-network theory*, he defines that an actor, or actant, is something that "acts or to which activity is granted by others" [55]. An actor-network is then an entity, an assemblage, that "does the tracing and the inscribing" of actors. Specifically, an actant, as the source of an action, can be anything and implies no special human motivation. Latour talked about the importance of including non-human actants in the process of understanding how power relations are formulated in society, and suggested that we could see actors as something unstable, including ourselves so that during our examination of a social assemblage, we can try to align our points of view with actors [56]. To Latour, ANT is a method or a tool that we can use to describe social phenomena, but it does not provide an explanation or answers for them. Just like how physicists record the momentum and position of particles in their experiments before they can find patterns, Latour tries to define each actant by a list of actions upon others to which it is linked. He said:

> "An actant is a list of answers to trials – a list which, once stabilized, is hooked to a name of a thing and to a substance. This substance acts as a subject to all the predicates – in other words, it is made the origin of actions…The longer the list, the more active the actor is. The more variations that exist among the actors to which it is linked, the more polymorphous our actor is." [56]

Being stabilized here means that a thing can get named as an object from its actions, having a consensual definition that we no longer negotiate with, but it also means domination is exerted. In Latour's eyes, everything, either human or non-human, can be described as an actant. But upon the increase of its actions with others, it starts to distinguish and formulate unique patterns that we may then be able to deduce its performance from competence and predict its possible state of associations.

Latour's notion of actant also poses a challenge to the anthropocentrist view that is often seen in social science. Both human and non-human actants come into existence at the same abstract horizon before performing different actions. This initial equality eliminates the priority of humans over other non-humans. As the impact of an actor is determined by their actions, non-human matters, if well linked with many other actors, can possibly be of more importance than a human actor who has very little to do with others. This idea was further pushed by political theorist and philosopher Jane Bennett into a more powerful narrative as the "political ecology of things". Bennett proposed two terms to highlight the often neglected active role of non-human actants in public life – *thing-power* and *out-side*. She said:

> "Thing-power gestures toward the strange ability of ordinary, man-made items to exceed their status as objects and to manifest traces of independence or aliveness, constituting the outside of our own experience. I look at how found objects (my examples come from litter on the street, a toy creature in a Kakfa story, a technical gadget used in criminal investigation) can become vibrant things with a certain effectivity of their own, a perhaps small but irreducible degree of independence from the words, images, and feelings they provoke in us. I present this as a liveliness intrinsic to the materiality of the thing formerly known as an object." [57]

Bennett draws inspiration from "small agencies", a term by Charles Darwin, in our life such as worms, electrons, and stem cells, and considers them as actants. These actants when in the right "confederation" or assemblage can make big things happen. Different from a phenomenological approach that centers around human experience, Bennett did not stop at looking at an actant simply as a source of action but looked further into its intrinsic power, the energetic vitality, and ascribed agency to it by a touch of anthropomorphism. Just like humans that have various intentions, non-human actants also have various types of vitality that make them actively or passively participate in an actor-network. The result of this outward-looking into the non-human domain and agency ascription is a minimized gap between the meaning of a political system and that of an ecosystem. In Bennett's view, there is a political ecology in which "persons, worms, leaves, bacteria, metals, and hurricanes have different types and degrees of power" as participants [57].

While Jane Bennett's actant with thing-power can be considered a search for an ideal potential democratic assemblage of the broader scope by acknowledging non-humans in more ways, Karen Barad proposed another way to approach actant by her novel definition of "agency" from a quantum physicist perspective in understanding how our reality is constituted. She names her theory *agential realism*. Different from the agency by Latour [58] or Bennett that serves as a property ascribed to an actant or an object, Barad reworks on the notion of agency and emphasizes that agency is “an enactment, a matter of possibilities for reconfiguring entanglements [59].” She completely rejects a humanist view of agency and sees it as possibility of “mutual response, of worldly reconfiguring, to attend to power imbalances.” Barad uses the word *entanglement* when she talks about her notion of agency, as her entire theory is structured on top of Niels Bohr’s epistemological framework. Therefore, to better understand this notion, we may need to think of agency at an atomic level before projecting it onto a larger social space.

In quantum mechanics, particles such as electrons and photons sealed in an isolated system are in a superposition, an indeterminate state that their properties (momentum, position, etc.) cannot be determined before measurement [60]. It is not because of our lack of knowledge or methods to measure these properties, but because any measurement apparatus we use on the quantum system will entangle with it and the measurement apparatus itself will contribute to measured outcome. Entanglement here is a unique phenomenon in quantum mechanics where the behaviors of particles can have a perfect correlation. When entangled, these particles exist as an inseparable whole that any of them cannot be described independently of the state of the others, even if they are spatially distant from each other [61]. So whenever we try to measure the quantum system, we the observer also become entangled with the system (see Figure 3). At the same time, this measurement breaks the isolation of a quantum system, introducing decoherence into the system and causing the vanishing of the superposition of these particles. The result is the collapse of a quantum system into a mixture of classical states, whose values are determined partially by the way we use to observe as well as the superposition state it held before vanishing [62] [63].

Barad's idea of agency mainly comes from this unique phenomenon of property emergence via interaction. She used a neologism *intra-action* to describe this co-constitutive effect of agencies as:

> "A phenomenon is a specific intra-action of an 'object' and the 'measuring agencies'; the object and the measuring agencies emerge from, rather than precede, the intra-action that produces them. Crucially, then, we should understand phenomena not as objects-in-themselves, or as perceived objects (in the Kantian or phenomenological sense), but as specific intra-actions." [10]

In some sense, Barad took a similar stance to Latour that the competence, or material configurations, of an object, occurs after its performance [64]. However, Barad thinks this performance *always* precedes competence, different from Latour's view that, at a certain point, actants can be stabilized into objects and start to deduce performance. At the same time, what is unique about Barad's idea is that there is a non-localized correlation embedded in the agencies. Just like how we can always get correlated results upon measuring entangled quantum systems, objects get correlated material properties upon their intra-action, as a result of their entangled agencies. Following this non-locality of agencies, objects are no longer considered independent, self-contained existences, and are only distinct in relation to their mutual entanglement.

From Latour's ANT to Bennett's political ecology and to Barad's agential realism, we can see a picture of reality that is networked and entangled. Our reality is complex and full of different types of actants and power relationships in between. Taking the principles and essence of these social theories, my research aims at designing a relational virtual reality space of similar essential qualities. Participant interactions are not just technical terms in my work but are designed as the performativity of participating agents, either human or non-human, from which meaning can emerge.

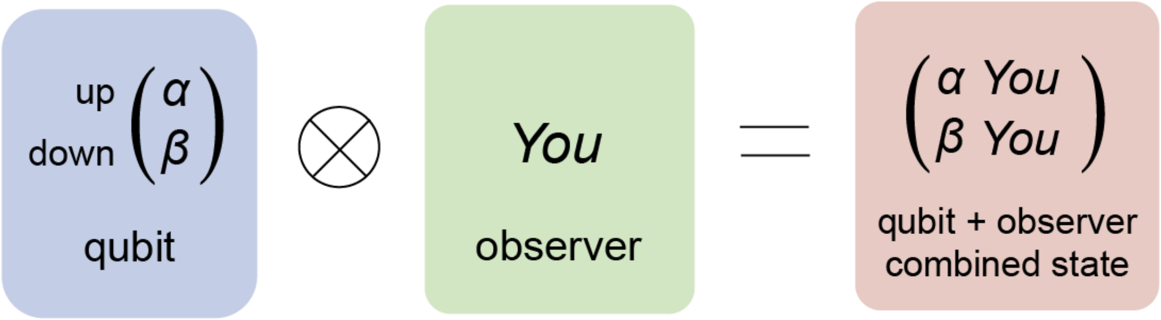


Figure 3. A conceptual illustration of how we as an observer may entangle with a quantum system.

2.5 Interactive Storytelling

Interactive storytelling refers to a narrative experience in which the rendering of the storyline is not predetermined but corresponds to the audience's navigation or interaction. This idea can be dated back to as early as the 1940s in Jorge Luis Borges's *The Garden of Forking Paths*, a fictional story in which he described a labyrinthine novel of complex branching structures and of multiverse-like parallels following different chains of causes [65]. A few decades after Borges's story, this type of labyrinthine novel became widely available in real life. Choose-Your-Own-Adventures (CYOS) story books invented by Edward Packard started to be popular as gamebooks for children in the 1970s. The readers of the book can make choices for the main character and determine the story's outcomes. At about the same time, with technological innovation in natural language processing and computer system, the digital version of this type of story, interactive fiction (IF), also appeared, such as *Colossal Cave Adventure* (1976) and *Zork* (1977) [66]. Allowing the audience to type in words and text to drive the actions of the main character, IF provides a stronger sense of freedom and realism in the exploration of the story than its analog counterpart, turning a story into a dynamic experience full of many different types of possible actions. In some IF stories, an action by the audience can lead to subsequent new actions becoming available, guiding the audience to step into a dramatically different story branch that is unique and highly personalized. Along with its followers, such as web-based hypertext fiction and visual novels, IF nowadays has evolved into more diverse forms that involve not only text but also animated graphics and sounds. Some of them have even developed into part-game part-story experiences, blurring the boundary between role-playing games and storytelling.

In 1997, Janet Murray published her *Hamlet on the Holodeck*, a book in which she explored the unique properties and influences of digital environments on classical narratives, and provided her own vision of the future of interactive storytelling. Murray's vision of an ideal form of storytelling can be said to be simple yet possible – a Star Trek holodeck-like system that immerses humans into photorealistic virtual reality and renders a whole dynamic space of intelligent and interactable characters. To Murray, interactive storytelling is about this immersive simulation, creating a virtual world full of interrelated entities that the audience can enter, manipulate, and observe [38]. By examining classical stories, she thinks that an interactive narrative experience should have a particular focus on the representation of a story world instead of the rendering of an individual story. Her idea of a story world encompasses a whole ecosystem of characters, places, objects, events, and rules, and all of them contribute to the happening of an individual story. A very important aspect in the successful representation of a story world is the behavioral patterns and patterns of interrelationships of characters. She said:

> "Fantasy fiction like *Lord of the Rings*, *Harry Potter*, *Game of Thrones*, *Star Trek*, and *Star Wars* all have their own highly recognizable storyworlds. But so do more realistic fictions such as Jane Austen's or Charles Dickens's novels or the *Gray's Anatomy* or *House* TV series. These storyworlds are defined by more than just a particular geography or set of characters; they exhibit formulaic patterns of cause and effect that create dramatic expectations about the kinds of things that are likely to happen to the people in the story, and the ways they might respond to events." [38]

These patterns of cause and effect in Murray's perspective are central to maintaining the coherence of variations in a story world. Especially when the audience is given the chance to provide custom input that can cause a direct or indirect impact on the story, the interactive system must be able to understand and interpret this input in a reasonable way so that it does not break the audience's expectation of proper responses.

Following Murray's idea of a holodeck experience, we may see that the state of the art in interactive storytelling is mainly role-playing video games, even though the majority of these games are for entertainment and are less focused on storytelling. Commercial games such as *The Legend of Zelda: Breath of the Wild (2017)* [67], *Grand Theft Auto V (2013)* [68], and *Cyberpunk 2077 (2020)* [69] are all designed as open worlds in which the player can roam around a borderless fictional landscape and follow the instructions from virtual characters to go through and complete different quests as a way to experience the narratives. On the one hand, these games provide a huge number of characters and sub-storylines that the player can spend hundreds of hours exploring those visually stunning story worlds. On the other hand, although the player is given flexible ways to interact with the virtual environment and characters, the main storylines are often not impacted by the player's behaviors or they just switch between a few different branches. The player has the freedom to interact but does not have the freedom to change the fate determined by the game designer. Indie games such as *Darfur is Dying (2006)* [70], *Papers Please (2013)* [71], and *This War of Mine (2014)* [72] provide better narrative experiences than commercial games as the main goals of these games are less about consumption and more about making a serious expression or even advocacy on certain themes such as wars, politics, and social issues. Such games may not be as visually appealing as commercial ones, but they often have a specific focus on rendering narrative elements that are direct results of the player’s choices as well as the interrelationships between the player and game characters.

While it might be easy to point out the gap between existing interactive narratives and an ideal holodeck system, it can be a difficult task to design a good interactive story. As a hybrid product of computer software and narratology, interactive storytelling is indeed a domain of high technical barriers. During the composition process, the creator needs to think logically and procedurally in designing an interactive system with branching structures of the plots, while also producing vivid and engaging storylines and narrative details that can captivate the audience. This process can be highly challenging as the creator frequently switches between two modes of thinking, storytelling and programming, in order to fulfill the requirement of building an interactive story. Murray described this challenge in authorship as:

> “Procedural literacy – familiarity with programming concepts and facility with specific programming environments – has increased in the past decade, but there is still a large gap between the storyteller and the programmer, and the hacker-bard with equal competence in both areas remain rare. The key to expanding opportunities for the procedural authorship of multisequential and multiform stories is to put the processing power of the computer in the hands of the author.” [38]

Murray thinks that most of the existing interactive storytelling experiences often just provide one route for the audience to go through. Even if the experience does offer choice points leading to variant plot events, it is usually constructed with only shallow detours off the main route. To be able to create many routes that branch into significantly different directions, human creators have to design each branch separately, which requires tremendous effort. Therefore, a computer storyteller needs to be introduced to accelerate a computational creation process. While such a system can fill the gap between technicality and creativity, it is not yet available to creators.

Existing methods for a computer storyteller mostly focus on developing AI algorithms to drive virtual characters or planning algorithms to procedurally generate possible trajectories of the story. Computer scientist Mark Riedl described three different departure points of the existing interactive storytelling systems that researchers have been working on – 1) authorial intent, 2) virtual character autonomy, 3) player modeling [73]. The **authorial intent** approach centers around the author's storytelling intent to define the possible space of narrative experiences. These systems often use a branching story graph in which each node represents a story fragment written by the author, and the directed arcs are choices to be made by the audience. Under this structure, the author has the greatest responsibility for storytelling as the audience's choices of interactions and their impact are all pre-determined by the author. **Virtual character autonomy** focuses on rendering stories by autonomous virtual characters and their behaviors. Researchers often design and develop AI algorithms for the characters to simulate their personalities, mental states, or social relations as decision-making mechanisms to drive their behaviors and interactions with the audience. Particularly, Riedl mentioned that, when the virtual characters have complete autonomy, an interactive narrative can be considered an *emergent narrative*, and there is no need to guide the audience's narrative experience toward a certain goal. **Player modeling** shifts the storytelling focus from narrative content designed by the author to the preferences or intent of the audience. This approach tries to adapt the narrative elements to respond to user actions, maximizing the personalization of a narrative experience. All three directions have resulted in interesting storytelling projects, while most of the existing video games tend to lean towards a combination of the first and second approaches for rendering narrative content. Very few attempts have been made in the third direction, but it certainly has a huge potential in delivering a new type of interactive storytelling for its audience-centric narrative strategy that can lead to highly unique and dynamic experience.

If we look at Murray’s holodeck dream together with Riedl’s summary of existing interactive storytelling system techniques, we may find that perhaps a holodeck system is not impossible if we can find ways to combine virtual character autonomy and player modeling. In my research, I specifically focus on producing emergent narratives by autonomous virtual agents while also applying audience-centric strategies to create dynamic and responsive story worlds, so that every audience interaction matters in my virtual environments, which can possibly lead to unexpected but pleasing narrative effects.

2.6 AR & VR Authoring Tools

One of the biggest challenges for artists today in integrating immersive elements into their artworks is the technical barrier to designing and creating AR and VR experiences. Unlike many other new media creative areas such as photography, filming, animation, or music production that there are several existing easy-to-use tools for artists to quickly start with, the creation of AR/VR experiences lacks a standardized pipeline as well as a single platform that can integrate all different aspects of a production. As the nature of a work of AR/VR is essentially about creating a new reality that is either realistic or fictional, the workflow often involves efforts in building 3D modeling, animation, user interaction, spatial interface, and advanced features such as voice or gesture recognition, and natural language processing, all of which require strong technical expertise. Given this requirement of diverse skills but a lack of integrated solutions, artists and creators often need to rely on a game development pipeline and work with a professional team of distributed expertise. Michael Nebeling commented about the trouble with existing AR/VR authoring tools as:

> "While tools like Unity and A-Frame have in many ways become the 'standard for AR/VR,' they still provide a high threshold for non-technical designers and are inaccessible to less experienced end-users. There is a new class of tools for creating basic AR/VR experiences, allowing users to choose from pre-made 3D models and existing scripts for animation and interactivity. However, these tools usually cover only a very limited spectrum of the AR/VR design space and still require programming for more advanced application logic." [74]

Nebeling thinks that there is a huge design space we can explore in the domain of AR/VR, but it also results in a massive tool landscape of various different software that makes it difficult even for experienced creators and developers to get used to them. Between tools or within tools, there are also significant gaps for the creators to smoothly connect different steps or make parts compatible, making it even harder to iterate or prototype ideas. Nebeling then proposed criteria regarding the optimal tools for AR and VR design based on two factors – level of fidelity and level of technical resources requirement. Nebeling used this as a simple framework to classify the existing tools, with the goal to point toward a future direction of tool design. Essentially, one should expect an authoring system to let creators produce high-fidelity AR/VR experiences while requiring the least amount of technical skills and resources from the creators.

While fidelity is a desired aspect in tool design as it deals with the overall outcome of AR/VR authoring, it is also necessary to look at the creative process in general and see how it impacts the design of tools. Donald A, Schon's design ontology discusses the process of design as a "reflective conversation" with the materials, in which a designer works by a cognitive pattern of "seeing-moving-seeing" [75]. That is, a designer identifies and recognizes the patterns and problems of an object in a situation, modifies this object based on the findings, and then comes back to identify new patterns in an iterative manner. This theory well applies to different material-based creative practices such as architecture, furniture, and industrial design. In the domain of software-based design, however, it becomes a challenge to support this reflective conversation between the designer and the virtual software material. A typical workflow nowadays in the technology industry is to let the designers communicate with the developers, who serve as agencies to modify the core material of the software. This obviously becomes a problem as the designers can easily struggle to describe their design to the developers using abstract concepts, diagrams, or mockups without missing details or leading to misunderstandings, due to the differences of expertise. Ozenc et al. in 2010 introduced their workshop study on how to support designers in the context of software tooling. The study particularly showed the communication barrier between designers and developers, and their suggestion for future tool makers targeting the creative process was to include more interactive controls that can help establish a direct conversation between designers and software material [76]. Specifically, they characterized four aspects of interactive controls to consider in tool design: 1) affordance, 2) feedforward, 3) expression, 4) feedback. **Affordance** communicates with the designer what actions they are capable of taking. In Don Norman’s view of affordance in design, a good tool should demonstrate coherence and understandability through an explicit conceptual model to ensure that the desired and relevant actions are perceivable [77]. **Feedforward** communicates the potential outcome of an action before the action is taken. It focuses on the coupling between the designer’s action and the target object’s function, which allows an intuitive interaction [78]. **Expression** determines the capacity of the designer to express their intention to the system. For designers, it is often important to keep their most familiar ways of expression based on their creative practice, such as sketching and drawing, hand sculpting, and natural language, instead of following the expression of the computing system by code and data [79] [80]. **Feedback** communicates the system's recognition of the designer's input action, and serves as a natural consequence of this action. Good feedback often conveys the information directly or indirectly associated with the function of the system, and also provides some extra sensorial character of the interaction such as haptics and sound [78].

While these aspects of interactive controls in tool design can help us think of and evaluate the capabilities of a new interface for authoring, there are specific AR/VR related challenges that are unresolved and need additional research efforts. Ashtari et al. did a comprehensive interview study in 2020 to understand the major challenges in AR/VR authoring, with a particular focus on creators who are non-professional developers of various backgrounds, such as professional designers, domain experts (psychologists, linguists, etc.) and hobbyists [81]. Their study particularly pointed out issues in existing AR/VR authoring practice that the future tool should attempt to resolve such as the lack of guidelines and workflow for creators to begin within the tools and the need for design assistance for story-driven interactive experiences. The biggest challenges remain in the implementation stage, where the authors described there are too many unknowns for the creators and a lack of flexibility in supporting diverse interactions. In short, the existing platforms and tools have several milestones to achieve before they can fulfill the creators' needs in designing and building interactive immersive experiences.

My research specifically focuses on filling the gap between the goal of interactive AR/VR storytelling and the authoring process. Artists and storytellers like any other designers work in a reflective pattern and frequently need to communicate with the AR/VR software. By providing reactive and dynamic visual interfaces that offer instant feedback on their design actions, my toolkits aim to support a wider range of creative practices than existing tools and a smoother learning experience for creators. My work also lowers the technical bar of creating interactive AR/VR scenes and stories that enables creators with no programming experience to easily create narrative experiences with diverse interactions in a virtual environment.

3. RELATIONAL REALITY

Virtual reality can be considered a synthetic reality simulated by a computer that extends beyond our real-world environment. A virtual relation, in the same way, can be considered a synthetic version of a real one. It may or may not be exactly the same as what we often perceive or experience in real life, but it must exhibit some features that are possessed by or commonly seen in real relations so that we can still recognize it as a type of relation. But what are these features? How do we synthesize a virtual relation? This chapter provides a conceptual foundation for creating relations in virtual reality. The concepts presented in this chapter are built on two goals: 1) to enhance the user's sense of plausibility in a virtual space, 2) to help creators design and deliver new kinds of relations in ways that plausibility is not broken. In order to deliver a sense of plausibility about relations, I propose that we first look at how relations are often understood and perceived in our real life, and then extend this knowledge into the virtual domain. Taking inspiration from prior works in philosophy, sociology, computer science, and media arts, I aim to draw a clear picture of what a relational reality is, and how we may design an experience that incorporates relations between various entities.

3.1 Relations

Our life is full of relations. Every one of us is related in some way to others, to the environment, and to the socioeconomic system around us. However, a relation, unlike a tangible object or substance, can hardly be captured or measured. Even though we do often perceive its presence between things and events, and between various entities, we do not quite have a formal and universal theory of relations. If we think of the types of relations we encounter in our life, we may realize the existence of various relations – they can be physical, social, logical, psychological, biological, etc. Such a variety of relations lacking explicit commonalities has made it even more difficult for us to theoretically describe what relations are, and to systematically think of the possibilities of relation occurrence [82].

If we look at some of the contemporary discourses on relations, we may find that philosophers have also been puzzled by the ontology of relations for a long time. Their debates mostly center around a very fundamental question – should a relation be considered as an object or as a property of an object [83]? A common dilemma they face in trying to answer this question is that, if a relation is considered an object or a substance, then for its dependency on its relata, a relation object will not follow along with the self-contained nature of an object in the essentialist tradition [84]. However, if a relation is to be considered a property, then since a relation often holds between two or more objects, this relation as a property will need to belong to multiple objects at the same time, having more than one object as its property bearer. This will destabilize the common definition of a property as something exclusive to a single object. Therefore, no matter which way they choose to place relations, it will pose challenges to the composition of an essentialist ontology. For this reason, reductionist philosophers tend to get rid of relations from their fundamental ontology, and think of them as either "creatures of reason and mental comparisons" or "reducible to nonrelational features of relata" [84]. Relations, following this way of thinking, may not even need to exist.

This certainly appears to be against our common sense and may not be practically useful for anyone who tries to understand relations in real life. In fact, sociologists also find this essentialist and reductionist view of relations problematic, as it does not serve as a meaningful tool to explain how a complex social system may be constructed by relations between various objects and entities. Seeing this impracticality in the philosophical tradition, the prominent sociologist Bruno Latour advocated for an empirical metaphysics that reframes the way how we may approach the idea of object and relation by saying:

> "If we call metaphysics the discipline inspired by the philosophical tradition that purports to define the basic structure of the world, then empirical metaphysics is what the controversies over agencies lead to since they ceaselessly populate the world with new drives and, as ceaselessly, contest the existence of others. The question then becomes how to explore the actors' own metaphysics. Sociologists of the social have answered by abstaining from metaphysics altogether and by cutting all relations with philosophy, that fanciful and non-empirical discipline which represents the lowly infancy of the now mature social sciences. They have also strictly limited the set of agencies 'really acting' in the world so as to free actors from their delusion, prepare the ground for social engineering on a grand scale, and smooth the path toward modernization." [85]

For Latour, empirical studies are much more important than almost every philosophical work [86] [87]. An object that does not really act upon others in an empirical manner is a mere artifact of philosophical abstraction without much practical meaning. Given that, every object must be an actant first, and the actions it takes must have an impact or effect on other actant(s) so that this actant can be real to us. Following this idea, what is crucial to the empirical formation of an object is the relations that this object enters into [55]. Relations in the context given by Latour then can be considered traces of the actions performed by one actant onto another. They are unstable and shifting over time and space, and together they formulate a network from which we may discover sturdy patterns within this reality.

As I have briefly introduced the idea of actant within the framework of Actor-Network Theory (ANT) in Chapter 2.4, Latour believes that an actant can be described by a list of actions upon others to which it is linked. However, if we put together that an actant is nothing but a collection of actions, and relations are traces of these actions, does it mean that we can somehow describe relations by an actant or vice versa? Indeed, we can approach the idea of relations in this way, especially given that Latour himself also claimed that ANT is "an irreductionist and relationist ontology." Philosopher Graham Harman provided a concise summary of Latour's idea of an actant with a comparison to qualities, accidents, and relations:

> "Unlike a substance, an actant is not distinct from its qualities, since for Latour this would imply an indefensible featureless lump lying beneath its tangible properties. Also unlike a substance, actants do not differ from their accidents, since this would create a hierarchy in which some parts of the world were mere detritus floating on a deeper sea, and Latour's principle of democracy between actants would thereby be violated. And unlike a substance, actants are not different from their relations. Indeed, Latour's central thesis is that an actor is its relations. All features of an object belong to it; everything happens only once, at one time, in one place." [87]

Following Harman's reading of Latour, properties are no longer needed in our vocabularies to describe the ways in which an actant exists. They are just actions that relate to others. A property of having blue color, for instance, is an action of letting those of visual sensors detect or perceive blue color, or more precisely an action of absorbing, reflecting, and emitting blue light, while blue light is composed of photons, another actant assembled by a collection of individual actants in relations with each other traversing in space. It is worth noting that these actions are of no human intention. They are simply natural and material phenomena to us, empirically observable at different scopes such as fundamental particles and high-level social systems. Given the reappropriation of both properties and substance, as Harman suggested, we can understand an actor simply as its relations. In this way, our reality exists as a huge actor-network that is constructed on top of numerous relations. The only question left to be answered is: do we still need the idea of an object in this relational ontology? Isn't an actor also an object?

Rejecting the idea of an object's having essence beyond the empirical field, Latour thinks that relations precede an object, and so does an actant. For Latour, only when the relations we observe from an actant are stabilized, we are able to derive a fragile nature from the actant and turn it into what we call an object. Just like any empirical science, we deduce competence from performance. The name and the meaning of an object are not solid if the object does not have stable relations with others. Therefore, an object can be considered a stabilized actant and exist upon sturdy relations, though nothing is perpetually stable since every relation of an object is reliant on the presence of other actants. That is to say, in Latour's relational ontology, relations, no matter how sturdy they are, can only be used to trace the history of action events over time and space. It is always up to us to believe that the object we derived from the assemblages of relations is to persist or not in the future.

3.2 Practice

Following the ideas about different ontologies of relations, we are now able to think of how relations can be possibly incorporated into an interactive virtual reality system. But before we get into that, it will be useful if we look at the common strategies for composing an interactive virtual reality system. If we think of virtual reality as a complex multi-agent system composed of various agents such as human participants, intelligent characters, and dynamic or static objects, then, based on prior research in AI behavior design [88] [89] [90], software architecture [91] [92], and information systems [93], we will have two options to design such a system as an evolving program: a top-down approach and a bottom-up approach. For a top-down approach, we start by designing high-level ideas about the system (e.g., an ecosystem of artificial creatures, an alien planet of exotic civilization) to describe the top features we envision for the experience. With an abstract concept of the system in mind, we then place specific low-level elements that match the high-level structure into the virtual environment. This approach often provides a clear architecture where we can easily organize everything and handle more complex behaviors of different elements. Conversely, for a bottom-up approach, we start by designing lower-level elements (e.g., virtual characters, intelligent agents) as well as their behaviors in a discrete fashion, and then try to let them interact with each other to formulate emergent behaviors and phenomena. This approach may be less popular than the top-down approach since the low-level design can sometimes be ad-hoc without a clear organizing structure, but it allows more accurate and precise step-through of each element and makes it easy to configure each agent, maximizing the level of detail in the control.

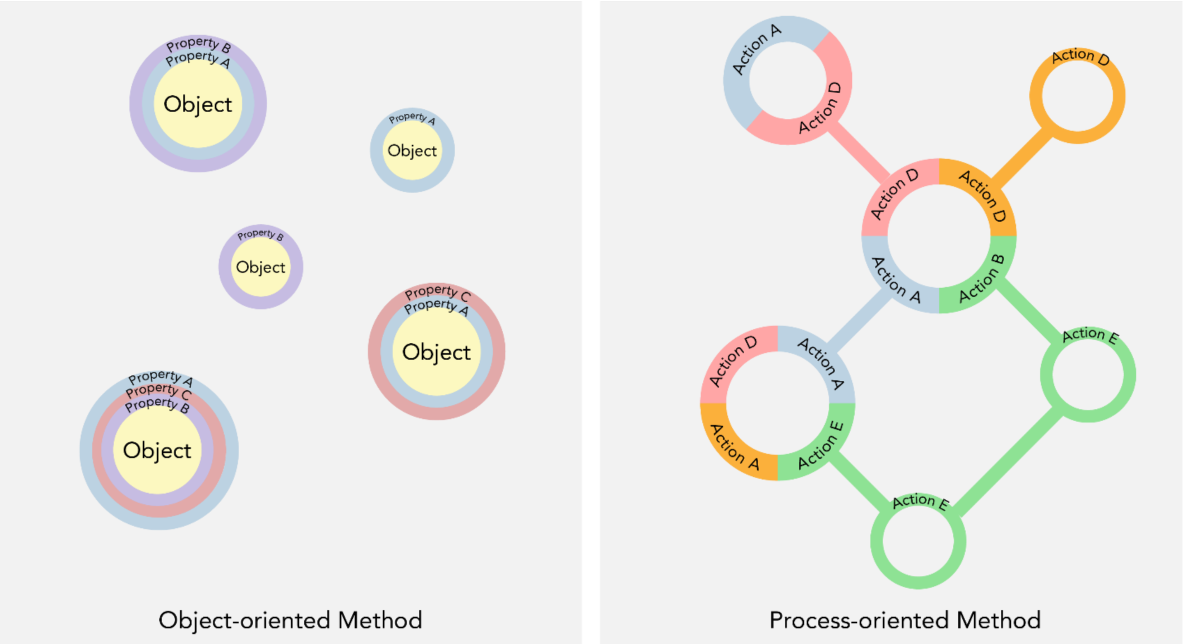
From a storytelling point of view, the top-down approach may work well with classical narrative strategies such as Joseph Campbell's Hero's Journey [94], Freytag's Pyramid [95], or Syd Field's Three Act Structure [96], as the system will be based on a high-level story arc of different stages. We will work with an abstract narrative structure and have a clear idea of how the entire system should look like. From there we can expand each narrative state (e.g., rise, climax, fall) by adding low-level interactive elements. For non-traditional storytelling, the bottom-up approach may be a good alternative to provide a simulationist style of the narratives, which is similar to Janet Murray's holodeck system for cyber drama [38]. Although this type of narrative may not be as controllable as the classical narratives because of the lack of high-level structural guidance, we can design the system to be highly interactive and unpredictable by various agent behaviors. A simulationist story also well supports interactivity such that upon each interaction, the audience may leave a short-term or long-term impact on the story. Then based on these different interaction impacts, we may easily have a large number of variations of the story development, leading to a highly plausible experience of the virtual world just like our real life.

These are just two brief system design concepts about composing interactive systems and narratives. The exact design and implementation of the experience can be very different if we use different methods to compose a virtual reality, especially if we approach the idea of relation in different ways. As we already know that we have two different ontologies about relations, an essentialist one and a relationist one, we can correspondingly derive two methods for us to design relations for a virtual reality experience: an object-oriented method and a process-oriented method.

For the first kind, an object-oriented method can be quite easy to think of – every virtual object is to be designed as an independent container of properties. Adding or removing objects will not affect other objects, and the system will be able to run with any number of objects, offering high flexibility. In a bottom-up system, one can scale up the virtual world by simply increasing the quantity and the variety of virtual objects. However, the virtual reality experience composed in this fashion may appear to be very "flat", as the objects are not tightly bound together by clear specifications of relations and dependencies. The essentialist encapsulation of a virtual object by an object-oriented method does not treat relations and interactions seriously enough to get to a standard for relations, making it difficult to upscale a complex system of emergent behaviors and meaningful structures. Many virtual objects may end up being autonomous or independent of each other, rendering a rather static scene to the audience. For creators who follow a reductionist view, relations are further reduced to properties intrinsic to a virtual object, making the process of designing relations immune to anything external to the object. In such a case, in order to design a relation between two objects, creators will need to speculate and predict how individual object movement may lead to a possible perception of relation by the audience, which adds extra overhead to the simulation process. On the other hand, in a top-down system, an object-oriented method allows the decomposition of high-level objects, by which we can potentially break down an object into multiple smaller objects. For instance, a human body can be decomposed into the head, neck, limbs, and torso, and a tree can be decomposed into a trunk, leaves, branches, and roots. The benefit of decomposition is that it may be useful to design and specify the details of an individual object, making them more expressive of clear structures in a virtual environment. But as relations between the components are not necessarily specified or included in lower-level objects, decomposition does not add relational details to the events in a story arc (e.g., how exactly one event relates to another) but only material details. Therefore, if we were to design a top-down system using an object-oriented method, then the virtual world we create may appear rich in material details but lack interactions between most of these details, as a result of continuous decomposition.

For the second kind, a process-oriented method focuses on the design of interactions between objects based on the idea that every object is an actant composed of actions in relation to others. These actions are directly associated with other actants instead of being held as intrinsic properties hidden from others. In a bottom-up system, we can think of the design of an object more by its behavioral quality, instead of by its material quality. For instance, if we were to design a virtual flower, we would first think of what actions this flower is capable of performing. If this flower is to bloom and release spores into the air, then we will give it openable petals that can store spores. If this flower is to hide behind the cliff instead of appearing in front of the audience, we then may not need to give it petals, leaves, or pedicels since its visual appearance does not participate in the process of interaction with others. Such a flower will still be considered a flower simply because of its blooming action, we do not need to design components of an object that do not relate to others unless they are part of the interactive process (though in most cases, visuals are always needed by the audience). In this way, we can design a virtual reality at a phenomenal level and prioritize the rich interconnectivity between everything. Every action we design is a perceptible phenomenon happening between two or more objects, and it provides the audience with a direct sense of relation in between. On the other hand, it is also easy to think of the design of user interaction for the audience to let them engage with the virtual environment. The audience can be considered as actants capable of performing actions in relation to others, just like many other non-human actants, so that they can actively disrupt or participate in the network of actions, freely navigating through the simulation process as they wish.

In a top-down system, a process-driven method will also provide us with some key advantages. Different from an object-oriented method where we use decomposition to break down a high-level object, we can use *differentiation* to break down a relational event into multiple actions and expand it with richer narrative details. When we are given a high-level action (e.g., a hero protects a village, a pandemic hits a country), we basically get to see a relational process of interaction between two actants. From there, we investigate the temporal and spatial aspects of this process and try to see if there are any local actants that may participate in this relation. If there are conceivable local actants, then we break down the process of an action into detailed actions in sequence to describe how each local action



Object-oriented Method

Process-oriented Method

Figure 4. A conceptual illustration of different design methods that may be applied to relational reality. Left: an object-oriented method that every object is an independent container of different properties. Right: a process-oriented method that every object is composed by its actions with others. The idea of an object is weakly constructed only for the purpose of taking interactions.

translates from one to another. In this way, a more detailed process of multiple actions can be rendered to reflect a more accurate and plausible situation of the original action. For instance, suppose we are designing a relational scenario that a village is accidentally on fire and some characters start to escape from the village. At a very high level, we may just design a village actant that is burning, causing the characters to move away from it. If we try to look at how this scenario is to be composed by local actants and actions, we may see that this relation between fire and people escaping can be differentiated into a process of more specific action steps over time: it starts with a small spark on a piece of wood, and then the wood gets burned and generates a large volume of smoke. More fire gets generated by the wood piece and starts to spread around to other furniture, items, and the entire house. Eventually, the entire house starts to burn with a loud noise, alerting the characters nearby who start to escape. Moving from one action to another, it may take many different intermediate steps to translate from an initial action to a final one. At each step, there are sometimes possible variations regarding the participating local actants who can cause the scenario to render differently. The more detailed steps we differentiate, the more mediation we add in between actions, making the entire translation process less predictable and more interruptible by external actants such as the audience who can participate in this process.

If we compare the two methods, a process-oriented method may appear more optimal for an interactive experience, as it thinks of a virtual environment as an actively changing dynamism constituted of various phenomena coming from diverse interactions. The object-oriented method tends to lead to a design of virtual objects by the “fictional essence” conceived of by the creator, but an object's essence does not necessarily lead to a phenomenon observable by the audience during the experience. For a top-down system, differentiation is also a powerful tool that allows us to think of each story event as a developing sequence of various actants’ interactions, unlocking more opportunities to turn a story into highly flexible pieces that we can embed more user interactions into the process of the story development. Almost every high-level story event can be somehow differentiated into lower-level action translations from one to another, and each translation can be potentially designed as an interaction point that the audience can control and manipulate. Again, if we think of the audience as actants who may perform actions to others, then we can always let the audience serve as the mediator between any of the actions in the differentiated action sequence. They can delay, accelerate, or pause the beginning of the next action that is necessary to move the story forward, or they can redirect the actants to step onto another path, determining which storyline takes place in the virtual reality.

3.3 Split Reality

While we, as creators, may use different methods to compose a virtual reality and design a variety of complex interactions between different virtual elements, the audience may not necessarily perceive the same reality as we do. Just like any artwork, there is always a gap between the rendering of the artist's intention behind the artistic expression and the audience's emotional feedback or intellectual understanding of the meaning of the work. A virtual reality experience is somehow similar to such an artwork – on one hand, there are a large number of elements and details that the creator tries to embed meaning into; on the other hand, there is highly subjective narrative content and relational phenomena that are to be perceived and activated by the audience. On top of that, there is also interactivity controlled by the audience that every audience may take on a unique and different path to walk through the entire experience, leading to more variations about how the narrative content is to be perceived. Therefore, to help us better understand the relation between these two different aspects of a virtual reality experience, we can think of an interactive narrative as a *split reality*, which holds both the "ontological" truth of a virtual world defined by the creator as well as the "phenomenological" truth with respect to the perceptual experience by the audience.

The term *split* is borrowed from object-oriented ontology (OOO), proposed by philosophers such as Graham Harman and Levi R. Bryant. Many OOO theorists today try to defend their essentialist idea that an object must have its essence and this essence differentiates the object from being the same as others, while at the same time they recognize some of the relationist views by Bruno Latour and Gille Deleuze that an object must be able to relate with others to appear real or to actualize itself so that it becomes perceptible to us. The result of this hybrid thinking is the split of an object, the epistemic distinction of internal dynamism enabled

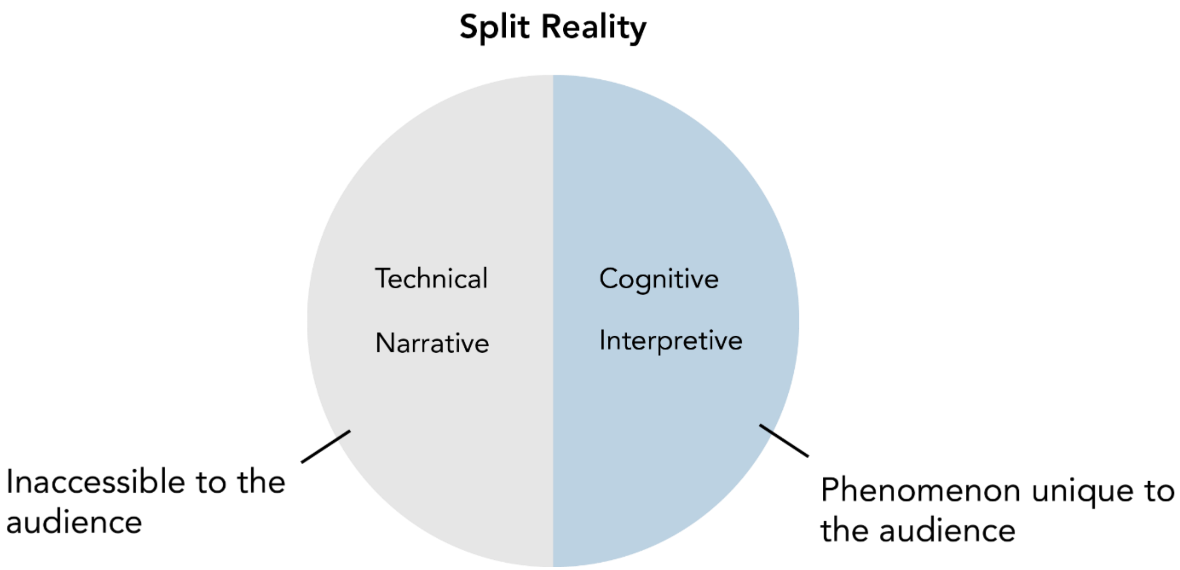


Figure 5. A concept drawing of split reality.

by the essence (inaccessible to us), and the changing relations it enters into with others (accessible to us) [97]. While OOO theorists try to use this idea of split to reason about how our material reality is composed, I will simply use it to describe how a virtual reality and an interactive narrative is made. Here, I recognize two types of split in a virtual reality narrative experience: 1) a technical-cognitive split, 2) a narrative - interpretive split. The former concerns the low-level composition of a virtual system, and the latter concerns the high-level meaning creation of an experience (see Figure 5).

3.3.1 Technical - Cognitive Split

For a digital simulation, the essence of a virtual object is its technical composition – its source code, the low-level program design, and the mechanism that makes this object properly exist and function in virtual reality. No matter how this object is behaving or rendering itself in a virtual environment, the audience will not be able to access its technical sources but only speculate about it. Similarly, the creators may design a highly complex code system for a virtual object, but the audience is not able to see this complexity, as there isn't a necessary association between the code and the audience's cognitive understanding of it. A complex program does not guarantee a vision of complexity, and a simple mechanism does not always lead to a perception of simplicity. Because of the inaccessibility to the blueprint of a virtual object, the audience will always be less knowledgeable about the simulated reality than its creators, and they will approach the fictional world differently from a non-technical point of view.

In contrast to the essence, there is also the relational manifestation of a virtual object. This includes the visuals, behaviors, or interactions that are exterior to the essence. It directly participates in the cognitive process of the audience toward this object. Unlike real life, the objects in virtual reality may take forms that are unfamiliar to the audience. They can be surreal, abstract, mathematical, or somewhere in between organic and artificial. Empirical knowledge from real life may not well apply here during the audience's cognitive process. It will be quite difficult for the audience to make a judgment or speculate about the qualities of a virtual object by only its visuals. For an easier and more complete understanding of a virtual object, the audience may learn about it through the relational phenomena – the actions the object performs to others or is being performed upon. For instance, suppose that we, as the audience, encounter a mysterious creature in a virtual environment. If we see the creature is made of flesh and bones, we may only infer that it is biologically made like any living animal. Besides that, there is not much useful information we can get to help us understand this mysterious creature. If we see the creature start to talk, we will then think of this creature as an intelligent animal capable of communicating with humans or possibly a weird kind of parrot (if it looks not too different from a normal one). Therefore, unless it exhibits some more behaviors or interactions with its environment, our empirical knowledge about this creature will be confined to a certain level. What we need is to see as many actions as possible to get a better understanding of it. But at the same time, even if the creator has designed specific actions for us about this creature, until the moment these actions are exhibited, we are not able to get the full sense of it. Based on the way we experience these actions, there could still be some misunderstanding about the creature's design. Nevertheless, this cognitive process of learning about a mysterious creature is a unique experience for us, providing its own aesthetic value.

3.3.2 Narrative - Interpretive Split

From the technical-cognitive split, we can see that for every single virtual object, there is inevitably a gap between its design and its cognitive reception. If we look at a virtual reality experience, these gaps can get accumulated into a more serious rupture between the creator's goal of the experience design and the audience's reception. From a storytelling perspective, there is always an intended narrative thesis prepared by the storyteller, while at the same time, the right of interpretation is held by the audience. Especially, for an interactive experience, the narrative thesis may be quite vague and general as there are various ways to experience the story, while the audience often only chooses one path through it, holding a very specific interpretation of the story.

Just like the technical sources of a virtual object, the storyteller's intention behind an interactive narrative can only be guessed or speculated by the audience. The storyteller may have multiple goals for the narrative, but the audience may not see any or all of them. Even if the audience does think of a speculated goal that is close to the storyteller's, there is no way for the audience to verify this inside the virtual reality, unless the storyteller embeds this piece of information directly into the experience. Conversely, the interpretation of the narrative largely depends on the audience, as the spatiotemporal factors of interaction that activates the narrative content are in the hands of the audience. Therefore, the interpretations made by every audience can be largely different from each other, and may not align well with the creator's intended narratives.

3.3.3 Strategies to Hack the Split

Understanding this split can potentially help us as creators make better design choices about the low-level objects as well as the high-level narratives. If we were to take the audience into our consideration while creating an interactive virtual reality experience, then the gap between the creation process and the created outcome can be minimized. Here I propose three strategies that I use in my work to hack the split:

Design phenomena - The creators can take a phenomena-driven creation process to design the perceptual experience instead of simply designing the intrinsic properties of a virtual object. Every design choice made about the virtual object must serve a cognitive purpose. Any technical aspect of the design should be separated so that the creator may be less biased toward those technical components and mechanisms that are not to be perceived by the audience. When the creators are designing the virtual object from a technical point of view, then such technical knowledge may become transcendental to the creators when they are designing the actual behaviors and phenomena of the object, potentially leading to unwanted assumptions regarding how the audience may understand the object.

Perform Interpretive Testing - Just like any software system that there is a need for quality assurance testing, an interactive virtual reality also needs to be tested for the narrative purpose. If we take an immersive experience design as an artistic expression, then this expression needs to be proof-experienced to make sure that the narrative goal has been achieved. To evaluate this, one needs to be in the perspective of the audience as much as possible to test the experience that may be encountered by the audience. Certainly, there is no way to cover every possible case or path taken by the audience. One may also take an immersive creation process such as What You eXperience Is What You Get (WYXIWYG) [98] to compose the experience in the same perspective as the audience, though in this way there is a limited number of tools available for choice. For more specific testing methods, one may test at the unit level to examine individual components and objects, or one may test at the integration level to examine the relational translations of actions by individual objects. Both methods can provide additional insights into how the audience may interpret the narrative elements based on their choices of interaction.

Extend Virtual Reality - We often see virtual reality as an extension of our physical reality, but in a highly immersive environment where we have a strong sense of presence, the physical reality can actually be considered an extended reality with respect to the virtual reality we are immersed in. For the sake of mitigating the split between the creator’s reality and the audience’s reality, we can always embed more specific narrative intention-related content into the virtual space, such as multimedia materials in reality referenced during the narrative experience, the creator’s messages, or real-time communication channels. These methods can open the audience’s mind to let their narrative experience not be confined by the artificial virtual space, and connect them with a broader spectrum of the reality outside where they are so that more meaningful and more accurate narrative content can be delivered, though the creator also runs the risk of breaking the audience’s sense of presence by introducing anything external.

3.4 Participants

In a relational reality, for any actant, we may expect that there is some particular mechanism behind it that drives or stimulates a certain action at a certain point, just like how humans have various intentions to perform certain actions. In a virtual reality environment, we will have no problem with actions performed by human participants as they are simply driven by their intentions. But what about non-human actants? Do they have intentions or something similar to drive their actions?

If we try to simulate our virtual reality following our real-life scenario, many non-human actants (e.g., daily objects, machines, artifacts) are not considered capable of having any intention. Their performance of actions is propelled by other hidden actants or results of invisible driving forces at a microscopic material level. If we try to trace the causes of these actions or deduce these actions into low-level actants, we will perhaps end up with a highly materialistic virtual world composed of molecules or particles interacting with each other by physical forces. However, this way of thinking has two limits: the first is that we do not have enough computational power for such a highly realistic simulation, and second that we do not need this excessive level of detail to render a virtual reality, especially when this microscopic level phenomenon is not to be perceived. Therefore, simulating real life may not be the most optimal way to think of the mechanism behind a given actant. We cannot simply take what we know about our life into the design of virtual reality.

Instead of such a simulationist view, we may get back to our split reality view about objects. We may think of intentions as intrinsic driving forces that are part of the object’s essence. Compared to simulationist thinking, there are a couple of benefits of thinking in this way. The first is that we no longer hold the liability to give scientific reasoning of the force behind each action. A differentiation can be much more free-form since there is now intrinsic “thing-power” inside of each actant. Small objects may have a great impact. It will also be highly flexible to create and design fictional and imaginary actants. The second is that actions can be performed at any given point. As intentions are to be designed within the actant instead of being given by external actants, we can easily determine when and how each intention is to drive the performance of an action. In this way, we can achieve a level of autonomy for each actant, while still keeping a process-oriented way to compose a virtual reality.

As anything placed on the technical side of a split object is inaccessible to the audience, intention, in the same way, does not manifest itself to the audience. This results in a missed perception of intention by the audience, but at the same time, it also blurs the boundary between actions driven by human intention and those by non-human intention. Although we may expect that a human intention should come from a real person and a non-human intention should be just a simulated driving force, in a virtual reality it can be very difficult for the audience to tell whether an action is driven by human intention or non-human intention. For instance, suppose that we implemented a simple AI model that imitates human body movement in virtual reality. When we let this AI drive a human avatar to perform a series of body actions on a human participant, they likely are not able to determine whether these actions are driven by a real human or an AI model. The way to judge the difference depends on the access to the technical side of this avatar, which is blocked to the audience. In fact, in many online role-playing games, not only are NPCs sometimes mistaken for actual people by the players but also actual people are mistaken for NPCs.

Following the ideas above, we may reach quite an animistic view about the actants or participants in a relational reality, that there is not much difference between a human participant and a non-human participant, as both of them are actants driven by indiscernible intentions. For an AI agent imitating human behaviors, the more actions it performs, the more human it may appear to the audience. For a human participant in a social VR space, they may appear in the same way as an AI agent to another human participant – the more they perform, the more human they make another feel. Thus, as creators, we may not necessarily need to distinguish between human actions and non-human actions anymore when we design the phenomena of virtual reality. In this way, human and virtual agents can be equally placed in virtual reality to formulate a true democratic ecology. Our targets in a virtual social relationship will then be expanded from purely humans to humans and machines.

3.5 Principles

Since we have discussed key points about a relational reality and the possible benefits and opportunities brought to the creators, we can summarize the ideas into principles regarding the design and creation process of a relational experience:

- *Principle of Action* - Every object is to be designed as an actant capable of performing actions that have effects on other actants. The more actions an actant performs, the more real it appears to the audience. The more actants are related by an actant, the richer narrative it holds. Essential properties are permitted but they must serve the purpose of action performance.

- *Principle of Split* - Every object has its technical side hidden from the audience, as well as a phenomenal side exposed to the audience. The design and implementation of an object are better to be separated based on this split to avoid cross-over.
- *Principle of Phenomenon* - For a participant-centered experience design, one should prioritize the design of phenomena in virtual reality over a system-level simulation. Avoid excessive levels of detail that are not to be perceived.
- *Principle of Equality* - All actants equally exist, but they do not act equally. Actants are also participants in an experience, and participation does not require human intention.

In conclusion, this theory about relational reality investigates possible new ways of approaching virtual reality system design and virtual phenomenon simulation. The challenge of bringing relations into a virtual world while also keeping a participant-centered experience requires complex systems thinking. Therefore, the principles summarized here may help simplify and clarify the structure of a relational experience design. The larger goal then will be to investigate the practical implementation of action-based relation design as well as the design of new authoring tools that can support creators to think relationally about virtual reality.

4. RELATIONAL IMMERSION

Immersive technologies can help us establish new relationships with people, with virtual communities, and with virtual agents in a more natural manner. Newer interaction modalities brought by immersive technologies can be applied to social interactions with both human participants and intelligent agents, expanding our relation targets from purely human to humans and non-humans. In this chapter, I present two creative experiments that illustrate different techniques to enable relational immersive experiences for both human and non-human entities in virtual reality environments. *Biometric Visceral Interface* demonstrates the idea of remote and intimate connectivity between human participants, while *Eccentric Nature* shows the possibility of a virtual ecological system involving non-human artificial creatures.[1]

4.1 Introduction

Social interaction in a virtual reality environment is often limited to communication by voice and gestures between two digital avatars. While the fidelity of the visual appearance of these avatars may affect the participants' sense of presence and perceived quality of communication [99] [100], there is a limited number of works focusing on non-visual aspects

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[1] Biometric Visceral Interface presented in this chapter is based on the papers [293] [294]. The work is a collaboration with the papers' co-authors Jing Yan and Yin Yu.

of social interaction in a virtual environment. My artistic experiments broaden this idea of virtual social interaction by focusing on designing different relationships for the participants to engage within a virtual environment. I introduce design concepts of creating intimate relational links between human participants. I also provide artistic examples of an expanded social dimension that includes non-human agents as part of the virtual social dynamism. I demonstrate techniques for creating immersive experiences through a set of soft-robotic devices that stimulate participant interactions as well as a group of artificial creatures that invite participants to become part of a virtual ecological system.

Biometric Visceral Interface begins with a search for an alternative to the visual representation of biometric data and challenges the habit of seeing-as-consuming brought by the society of the spectacle [101]. This work is created as a design critique to disrupt the common practices of communication based on visual memory and quantified abstraction of biological phenomena. The aim of a set of visceral interfaces is to extend the human perception of their body to be able to associate and link with others to have a stronger shared empathy. *Eccentric Nature,* on the other hand, starts with a fictional cyberspace of imaginary artificial critters of social hierarchies. It is a search for emergent behaviors coming out of relationships and human interventions, and a deep dive into chaos, dynamism, and possibilities brought by algorithms.

4.2 Related Work

4.2.1 Social Interaction in Virtual Environment

The rise of internet culture made it possible for many people to simultaneously get connected in a shared virtual space such as a chatroom, or an online game. Ever since the

1990s, various technologies have been developed to enable social connections over the internet such as texts, voices, and videos. Early virtual social spaces, such as Second Life[2] and CyberTown [102], were mostly like MMORPG games where the users create avatars for themselves and then interact with other users within a shared virtual environment. Interaction methods were limited to texts, voices, and game-like activities. It was not until 2013 when VR technology became much more accessible to the consumer market that virtual reality as a social medium was conceptualized [103]. Higher fidelity social VR platforms then started to appear, such as Sansar[3], VR Chat[4], and AltspaceVR[5]. These platforms enable the users to immerse into content-rich virtual environments with a VR display to have a more embodied experience while interacting with other users located in different places.

Besides the major concepts that are explored in single-user VR experiences (see Chapter 2.2), the idea of social presence is often evaluated in a socially interactive experience in VR. Social presence can be defined, according to Frank Biocca, as “the degree to which a user feels access to the intelligence, intentions, and sensory impressions of another [104].” Similar to how the level of immersion interplays with an immersant’s sense of presence [25], the level of immersion also has a positive influence on the sense of social presence [105]. Back to Biocca’s definition of social presence, we may find that it left the interesting room about how this sense may be shaped as it is mainly about the traits displayed by other participants but does not necessarily require the actual presence of another human participant. Oh et al.’s systematic review of social presence also indicated that many different features in an interactive experience with human avatars or even social robots can influence the sense of social presence,

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[2] https://secondlife.com
[3] https://www.sansar.com
[4] https://hello.vrchat.com
[5] https://altvr.com/

such as identity cues, social cues, physical proximity, haptic feedback, visuals, etc. My experiments start with the exploration of different modalities and interactivity in an artistic context and investigate the possibility of enhancing a participant's social presence. Eccentric Nature lets the participant have access to the intelligence of virtual agents, while Biometric Visceral Interface amplifies the sensory impressions of another person in VR space, both of which provide novel ways of building relationships with others and giving the participant a sense of being with others.

4.2.2 Soft Robotics in VR

The application of soft robotics in VR is relatively new as this domain mainly originated from material science and structural engineering. Most of the soft robots are made of materials with moduli that are close to soft biological materials (muscles and skins) [106], based on Young's modulus describing the quantified relationship between compressive stress and strain. Therefore, the integration of soft-bodied robotic components into a VR system is often for the purpose of providing a more realistic haptic rendering of virtual objects, while also permitting flexible and safe interactions with human users in unpredictable physical environments [107]. According to Rus and Tolley, soft robotic actuators are usually realized in one of two ways: 1) variable length tendon structures that are supported by tension cables or shape-memory alloy (SMA) materials, 2) pneumatic structures with inflatable channels that can reach the desired deformation by air or liquid pressure [108]. For those devices that require direct skin contact with human users, pneumatic methods are often preferred as the deformation of the device can be powered by open-loop valve sequencing which provides more controllable actuation limits.

Various types of soft robotic devices for usage in VR have been proposed, and many of them focus on providing an improved sense of touch in form of wearables attached to the hand. For example, Jadhav et al. introduced a soft robotic glove for kinesthetic haptic feedback in VR environments. They designed a fluid-pneumatic haptic glove in the form of soft exoskeletons to provide force feedback to the fingers when the user is clicking a button in virtual environments [109]. More recently Baik et al. adopted a tendon-driven compliant robotic mechanism to provide both cutaneous and kinesthetic feedback to the user's fingers. The actuators were paired with force sensors so that they can exert accurate tension at the fingertips [110]. Besides haptic interaction with hands, soft robotics can also be used to render and simulate more types of interactive user behaviors in a virtual environment. Wang and Minor proposed and evaluated a bladder-based soft robotic smart shoe design that can provide an augmented sense of virtual terrain during the user's locomotion [111]. Project Butterfly synergizes VR Mirror Visual Feedback Therapy with soft robotic exoskeleton support to assist the user to perform a rehabilitative physical movement [112].

My work also adopts soft robotics as a way to augment human haptic senses in virtual reality. However, my approach not only looks at the functional aspect of this technology but also its visual and social implications, an extra design factor that promotes critical reflection about the possible cultural meaning of soft robotics.

4.2.3 Agent-Based Simulation

Computer simulation is popular in the natural science research and engineering process as most of the problems have been mathematically modeled by equations and formulas. However, for social science problems and especially phenomena related to human behaviors, simulation is often a challenging task as there are no detailed or clear mathematical models for one to predict the exact outcomes of complex interactions between different entities. Therefore, sociologists have proposed agent-based modeling to investigate the complex relationships between individual entities and their interactions, especially when the relationships between aggregate associations and individual agencies are implicit and unclear [113]. A typical agent-based model is built upon actual data on individual agent behaviors and then the researcher designs a computer program with an aim to generate new simulated data that approximates the real one. Some common properties that may be given to an agent representing an individual entity are birth, death, needs for resources, competition, perception, mobility, aggregating, etc. By going back and forth to find new properties or optimizing the weights of properties in the model, the researcher may be able to validate some hypotheses in the model and start to see and clarify the implicit causal relationships among different elements or agent properties. The model itself then starts to gain explanatory power about a social phenomenon.

This method has been proven to be useful in studying and revealing interdependencies between different human activities while also providing an ecological perspective on how a group of human and non-human entities is interwoven together as a whole [114]. Theoretical ecologist Robert May has been using agent-based models to investigate and understand the interactions between population changes of plants and animal species over time and space, with a particular focus on how human-created disturbance can have an impact on them [115]. Besides its practical usage in scientific discovery, computational social scientist Dirk Helbing also describes that agent-based computational modeling is well suited for visualization where we can build computer games based on it. Although computer games are not designed with the intention to understand or justify the outcome of a simulation or to draw conclusions or make predictions about certain real phenomena, they may take the same approach to deliver a believable experience with an underlying mechanism that appears as realistic as possible [116].

In the creative art domain, artists have been fascinated by the ideas enabled by agent-based simulation such as autonomous activity, emergence, and swarm behaviors. They often take inspiration from molecules [117], marine life [118], and human society [119] [120], to produce interactive and immersive experiences that the audience may find both visually and conceptually intriguing because of the believability of agent behaviors and complexity. My work *Eccentric Nature* continues this exploration on finding new agent-based models for artistic expressions but at the same time focuses on the audience participation in the simulation, where their behaviors can have a significant impact on the virtual environment. I am also inspired by this particular sociological method of investigating social phenomena that I utilize agent-based simulation in my storytelling to reveal the implicit properties and relationships between different virtual entities, by which a "virtual society" of high-level plausibility can be constructed.

4.3 Biometric Visceral Interface (2019)

Existing biometric technology has enabled people to observe and understand the biological events and state changes in their bodies. It provides a reliable and objective way by which various body phenomena can be converted into quantified information that is shareable among people. Biometric information in the form of data can be segmented, analyzed, interpolated, machine-learned, and fused in certain ways so that a meaningful and accurate description of a person's biological traits and conditions can be made interpretable. Virtual bodies or virtual avatars, on the other hand, serve as apparatus for people to inject themselves into a virtual environment. It often eliminates many of the biological traits of a person and represents their bodies in highly abstract forms, such as one-sized controller-like hands or an upper torso without legs. Existing HCI research works have informed us that an alternative body avatar in a virtual space that is different from a user's actual body can potentially cause significant behavioral changes in the user [121]. At the perceptual level, the plasticity of the brain can cause a person to change and adapt their body schema to a virtual avatar that is not consistent with their normal body proportions, especially when given a certain amount of multisensory and sensorimotor body information [122] [123]. At the social-psychological level, a virtual body is spontaneously considered by its owner not only as a part of themselves but also as a part of the virtual space, with the capacity to encounter and interact with others physically or socially [124] [125]. This gives us inspiration that mapping and exchanging biometric data between two users' virtual bodies may allow them to gain some new perceptual understanding about the virtual avatars they are embodied with, especially in relation to the biometric data's original owner. By letting them experience each other's biometric data, a possible sense of co-presence and perhaps a new remote but intimate relationship may become possible [126].

In this project, we present a set of soft robots along with an immersive social space to facilitate this type of biometric data exchanging experience in which sensation becomes a reciprocal action to each other, instead of passive reception. Two users of our system can feel and experience each other's virtual presence following a touch-like intimate pattern, and their biometric data is exchanged and projected to their bodies to formulate a feedback loop that continuously influences their concurrent perception. By this method, we investigate how affect may be conveyed and what new relationships can be established. We are also interested in the techniques of mapping, mediating, and transforming a user's biometric data to allow another

Figure 6. An overview of Biometric Visceral Interface system. (a) A user wearing a Biometric Visceral Interface and navigating in a computer-mediated virtual space. (b) A soft robot actuator on a user's neck. (c) A haptic link between the user and the device that incorporates pulse sensing on the user's ear.

user to gain some understanding of their partner's body through cutaneous senses. By introducing an intimate way of displaying biometric data via haptics instead of pure visual representation, we hope that a more "visceral" perception of others can be achieved, and it may increase our sense of co-presence in a virtual space. We name our new soft-robotic powered immersive system as Biometric Visceral Interface (BVI) (Figure 6) Visceral here stands for the innards of a body, and visceral perception throughout this paper refers to an intimate and immediate connection with others rooted deeply in one's virtual body. In the following description of the BVI system, we discuss the conceptual origin, design factors, system, initial results, and future directions of how soft robotics and VR technology can be used together to improve interpersonal communication and data visceralization.

4.3.1 Data Visceralization

The practice of data visceralization draws upon previous concepts explored in the domains of tangible media and affective communication [127]. It is concerned with conveying information through sensations of touch [128], scent [129], vibration, and warmth [127]. The major reason why we need data visceralization is that the effectiveness of visual communication can reach a certain limit when an intimate relationship is involved. As visual information is conveyed by human eyes without direct physical touch, intimate and emotional content can get lost because of the distance. That is, conventional information display methods by graphs and numbers, although, can describe the objective state of events with rich details, they cannot sufficiently express complex body states of affection and emotion [130]. When a more emotional interaction between two people is desired, haptic links between the users are often introduced to help resolve the delivery of such complex information [131] [132]. Simulating or recreating direct human touch, such as hugging, appears to be the most common form of communicating with affect. Many prior works have focused on the translation of audio or visual data into tactile stimulation, but they are mostly made as sensory assistance for people of disabilities [133, 134]. Data visceralization specifically focuses on the interpersonal and intimate aspects of social interaction and describes a comprehensive practice combining a diverse set of data rendering techniques to expand the dimension of how information can be possibly exchanged.

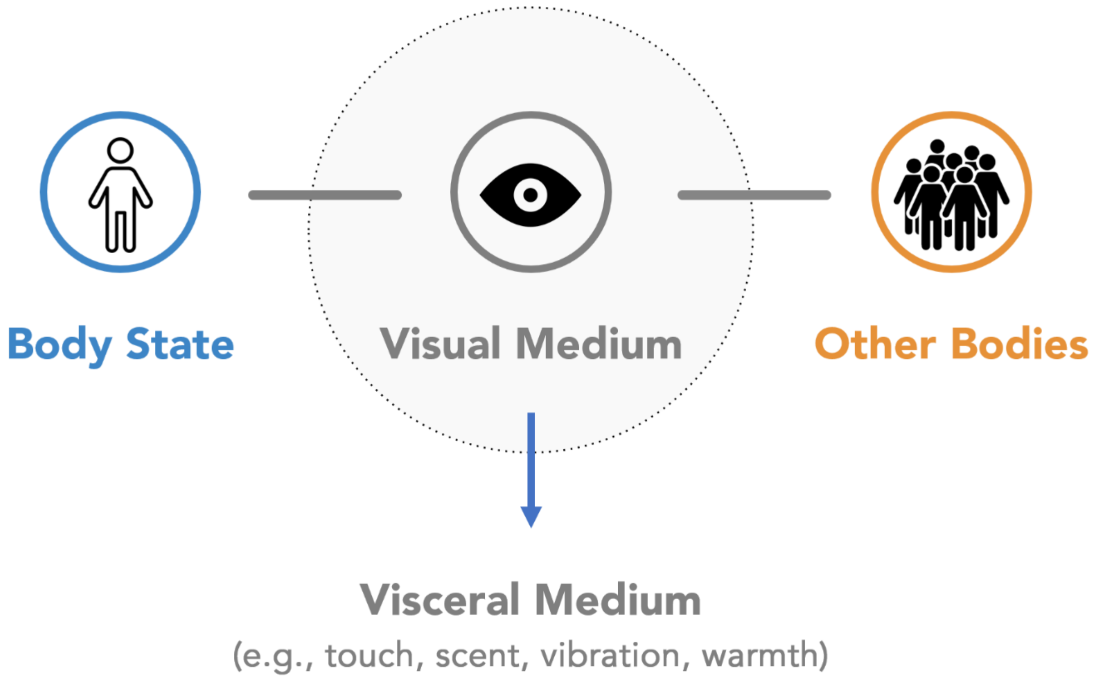

Figure 7. A brief diagram showing a visceral communication between individual body and other bodies.

4.3.2 Design Factors

We foresee a need for exploration and experimentation in haptic data representation in the context of affective interpersonal communication. Therefore, we propose a set of biomorphic designs of soft robotic prosthetic devices that provide users with a unique haptic experience dissimilar to the conventional optical reception of biometric data representation. We fabricate pneumatic soft devices as wearable interfaces that can fit on the human body, using commodity materials and electronics, such as pulse sensors and low-pressure air pumps. Extending a user's exteroceptive field like artificial organs, the devices we designed and their capacity to physically link two human bodies at the same time open up a new way of intimate but distant communication without direct skin contact of the users.

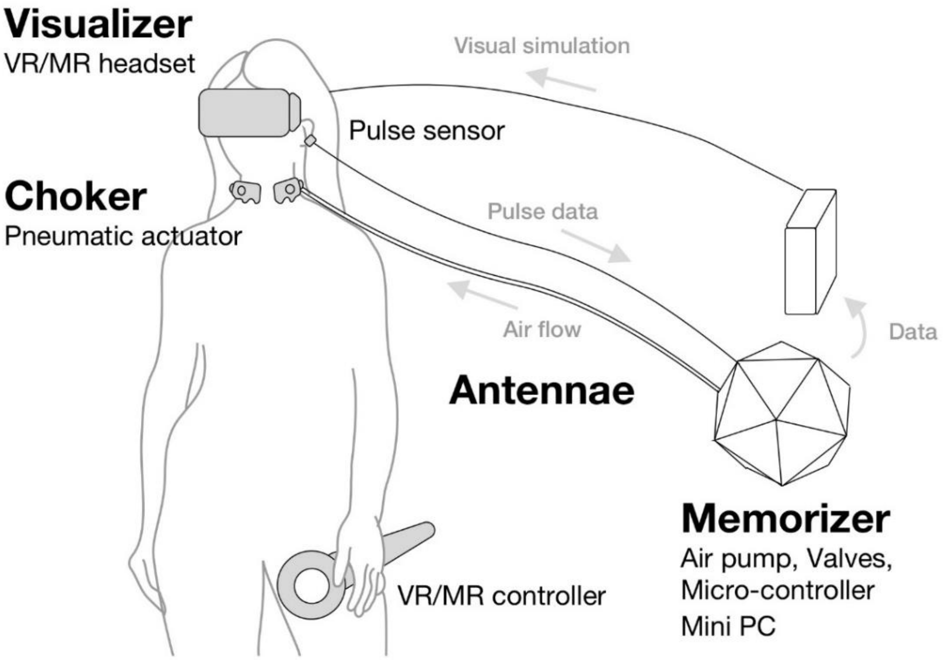

Figure 8. Installation Diagram of a Biometric Visceral Interface.

During the design phase for this research, we identified the following major design requirements: a) accurate and immediate biometric data collection from users, b) on-body pulse simulation and actuation, c) human-machine interface with data communication, d) modularity that users can easily detach themselves from the data exchanging network with other users, e) portability that allows a quick setup in a wide variety of social and private space. Given these design constraints, many large-scale technologies and skin-unfriendly materials were ruled out. For example, electro-active polymer (EAPs) could not be used because of the potential electric injury on the skin that may come from the high voltage it requires for effective shape-shifting. A large air compressor was also ruled out because extra calibration and safe operation would be required to be handled by a professional. After testing human skin sensitivity on different body areas and the air pressure required to actuate simulated pulse behaviors, we settled on a portable air pneumatic system of interconnected detachable components with low-power electronics and cast silicone.

In order to integrate an immersive visual experience to alter a user's self-body awareness, we also identified these design requirements: extended range of movement that the user can walk with the device in physical space, quick placement on body and release, hands-free biometric signal sensing and haptic actuation, networkability, and software integration for social VR applications. Especially, in a virtual environment, synchronization between the visual and the haptic elements must be prioritized in order to provide a coherent visuo-haptic experience. The physical mechanism of the BVI system needs to communicate with the VR system at latency as low as possible. Given the above constraints, we designed our BVI components with a focus on wearability, connectivity and visual synchronization (Figure 8).

4.3.3 System Components

A single set of Biometric Visceral Interface consists of four components: Memorizer, Choker, Antenna, and Visualizer. A memorizer, functioning as the central data apparatus and control unit, can have up to two chokers and two antennae connected to it. Each antenna links to a choker that is directly worn and attached to a user's neck. A visualizer is a wrapped VR//MR headset that works as a standalone component to provide visual immersion for the user.

Memorizer - The Memorizer, in this design iteration, serves as the data computation center and control mechanism. It handles jobs such as signal processing, pulse simulation, data communication, and virtual body rendering. The electronic peripherals embedded in a memorizer contain a mini air pump, a pair of valves, and an Arduino microcontroller. The

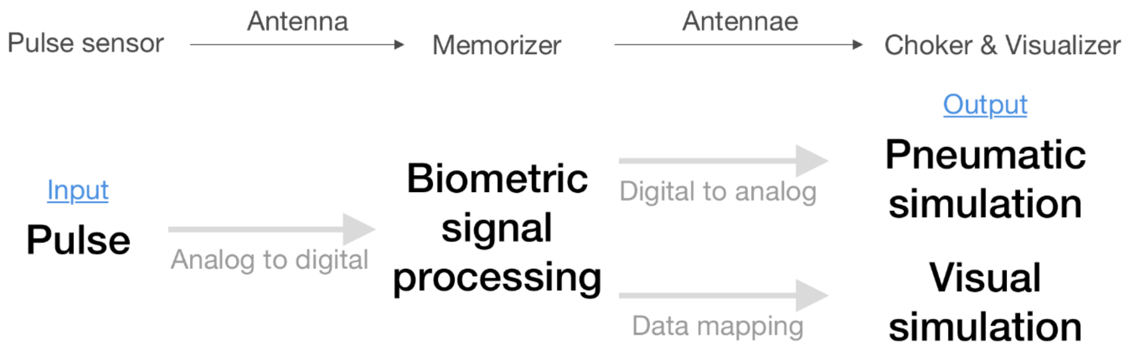

Figure 9. System Diagram of a Biometric Visceral Interface

visual computation is handled by a high-performance mini PC that has the processing power for VR graphics. The haptic mechanism and visual data representation are separately handled on two different processing units because we see the gap in computational workloads between the hardware and the software. The hardware control for the haptic interface requires very minimum computational power for signal processing and pulse simulation, as the pulse wave from a person can be easily converted to on/off signals for the valve system. We programmed a threshold-based switch that detects wave peaks to control the inflation pattern of the soft actuator. The ATmega328P microprocessor on the Arduino board is well capable of the amount of computational work on this part. While the microcontroller is controlling the haptic component, the sensor signal is transmitted to the mini PC unit via serial communication (or optionally via wireless connectivity) after acquiring the data. The serial rate is set to be 115200 bits/second which ensures a fast data transmission between the two units.

Choker - The Choker is a wearable soft haptic actuator that is to be worn on a user’s neck. We use silicon-based high performance rubbers to cast a soft and stretchable skin-safe pneumatic structure of varying degrees of elasticity (Figure 10). When compressed air is pumped from the memorizer, an array of air channels on the choker's surface will inflate or deflate to morphologically simulate pulsing movements. In order to make it simple for wearing, we place a bendable metal wire inside the choker so that it can quickly fit onto a user's neck and stay there by itself with a proper neck shape. Push-pull connection ports for air tubing are designed on the back for fast release from the whole system.

Antenna - The Antenna component is a cable-like multi-section connecting agent that links the memorizer, the choker, the visualizer, and the users. An antenna provides air flow transmission and data communication via air tubing and electrical wires. It is designed to fit with the push-pull connection ports of other components for quick setup. A pulse sensor with a clip is placed on one section of the antenna to sense a user's heart rate on her ear.

Visualizer - In order to integrate the VR system into our visceralization research, we added a new Visualizer component to the system (Figure 9). The visualizer, connected to the memorizer and placed on the user's head, serves as an entry point to immerse into the computer-mediated space. It renders and maps a virtual body onto the user to give her a perception of an alternative body presence. A visualizer supports the most recent VR technologies on the market such as HTC Vive and Oculus Rift that precise tracking is

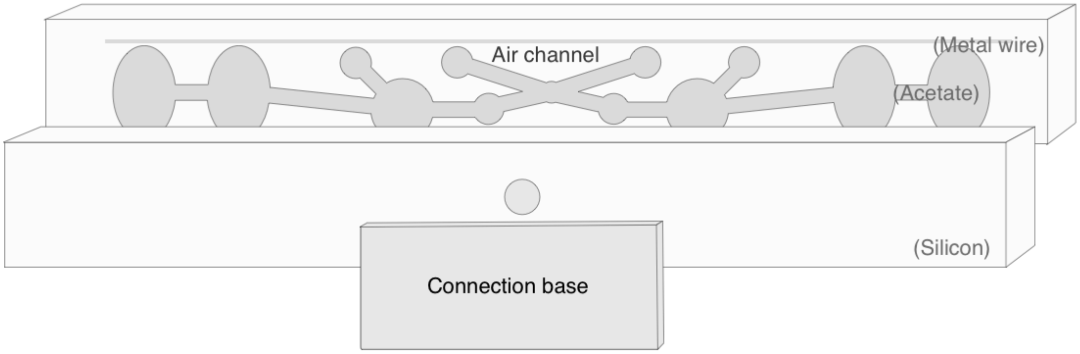

Figure 10. Structural design of the choker with air channels

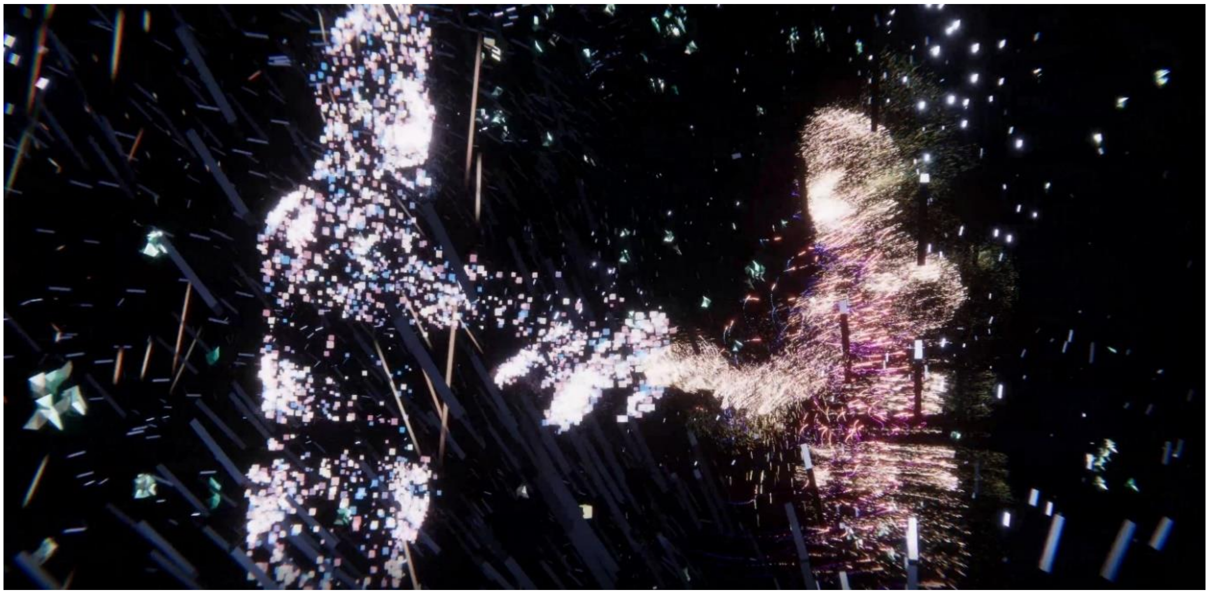

Figure 11. Voxel-based generative virtual body avatars the users can see themselves in a virtual space.

integrated to give the user a strong and responsive sense of immersion. We use the Unity game engine to generate real-time interactive 3D graphics in the visualizer, as Unity is well-optimized for high-quality stereoscopic rendering and for GPU-based parallel computing. We designed a voxel-based generative body avatar to induce the user to have an ownership illusion and to reconstruct the user's body schema. The pulse data is mapped onto the voxel particle flow that vibrates the virtual body to create an animated, dynamic and volatile sensation of visceral penetration beyond the body membrane (Figure 11). User orientation and positional tracking of the head and hands provide a visuomotor congruence between the real and virtual when the user is walking, rotating the body, and waving the hands. Placed inside an abstract and decontextualized space, the voxel-based virtual body is designed to enhance the user's level of immersion, so that the user can have a stronger sense of body ownership that takes her perception beyond the physical limits.

4.3.4 Interaction Modes

Two different operation modes are designed in our system: local mode and network mode. In local mode, users can experience either pulse data stored in the memorizer or a real-time signal directly from the pulse sensor on the antenna as the source of visual simulation and physical actuation. A single BVI system can be used by two users sharing one memorizer, although the system can deliver visual simulation to only one visualizer. In such a case, a visualizer and two sets of chokers and antennae, are connected to a memorizer. The two users, being physically in the same space, can sense each other via soft robotic actuation on their necks. An extra projection screen can be connected to the memorizer to share the content from the HMD.

In network mode, a single BVI system is used by each user and each device serves as a node in the network. A connected user can wear a BVI system and remotely sense another user's biometric signal in real-time. The memorizers telecommunicate with each other in the form of a remote visuo-haptic link. The computer-mediated space, in other words, becomes a social VR space where interactions are happening over the network. The users can encounter each other without being present in the same location.

4.3.5 Network Protocol

In order to reduce the bandwidth usage, we only send pulse data between the memorizer nodes over the internet. We use ZeroMQ[6] messaging interface with TCP protocol to achieve low-latency and reliable data sharing. Specifically, we use asynchronous publisher/subscriber mode in ZeroMQ so that the messaging nodes in the network are independent of each other

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[6] https://zeromq.org

and they can broadcast messages to others without making requests and responses. This allows the data to be transmitted with much lower latency.

4.3.6 Fabrication

We start with designing the dimension of a choker and its inner air channel. The total size of the choker is 32 cm (width) x 4 cm (length) x 0.6 cm (height). According to the previous air pneumatic model, we compute the approximate maximum air volume and specify the total area of air cells. With that in mind, we design a basic unified air bubble structure and test the tactual sensation of the choker on the user's neck. We find out that the back of the neck turns out to be more sensitive to haptic sensations, and conversely suppressing the front and side part of the neck would cause discomfort to users such as suffocation. Figure 10 shows an improved version of the air channel pattern and choker layers. The choker is fabricated with two visualization sections on the front and side of the neck with a leather layer attached inside facing outward and a haptic section on the back of the neck with another leather layer attached outside facing inward. Inside the haptic section, the air cells are made smaller compared to those of the visualization sections and are located upon the acupuncture points of the human neck to increase the comfort level and sensitivity of pressure.

The air pneumatic choker uses silicon as its main body material. Inside the silicon, a sheet of acetate was placed to create an inner air channel. The overall fabrication of a choker consists of five steps. First, we laser-cut acrylic boards and assemble the pieces to build the mold. Then laser cut a sheet of acetate according to the designed inner air channel structure (Figure 12. a). Once the mold and acetate are prepared, we then cast the elastomer. We mix a total of 48 *ml* of two-component elastomers (Smooth-On) in a 1:1 ratio (24 *ml* each) and pour the mix into the mold as the first layer of the choker. After the elastomer layer was cured, we placed the inner channel acetate on the top (Figure 12. Figure *12.* Fabrication process. (a) Laser-cut an acrylic mold and place first layer of silicone elastomer for actuator casting. (b) Place the acetate sheet on top of first layer. (c) Attach leather onto the silicone.b). Then we mix another same portion of elastomer and pour it into the mold as the second layer. Once the silicone was cured, we peel it out from the mold and attach a layer of leather onto its outside surface to enhance the inner side inflation and create a wearable aesthetic (Figure 12. c).

As the central data apparatus, a memorizer is able to hold the air pump and valve system, and a microcontroller. The design of the memorizer reflects the idea of neuro-bio-data centralization that it serves as a central connection for user interaction as well as a storage center for biometric data. A standard icosahedron with 20 equilateral triangular faces with each joint vertex formulating holes where the antenna and data cable can also go through.

The fabrication of the memorizer consists of 5 steps. We first laser cut the equilateral triangular acrylic pieces, each of which has an edge of 20 cm long and has three holes on each side (Figure 13). We assembled them together by tying them with fishing wire through the holes in this prototype. After assembling, we place the microcontroller, valve, and air pump inside the icosahedron memorizer (Figure 13. a). Before attaching the last piece of the panels, we thread all the cables and tubes through the vertices of the memorizer. The last step is connecting the memorizer and the choker with the antenna.

4.3.7 Air Flow Estimation

As we are simulating heartbeats on the choker that it needs to actuate at a frequency close to the human pulse rate, we need to estimate how fast the compressed air may flow into the choker's air channels to determine whether the choker's actuation rate meets our simulation requirement. Therefore, an important step is to find the relationship between the supplied air

$$p+\frac{1}{2}\rho v^2+\rho gh$$

pressure from the pump and the flow rate into the air cells on the choker. With knowledge of an estimated range of the flow rate, we use Bernoulli's equation to calculate the maximum

$$p_1+\frac{1}{2}\rho {v_1}^2+\rho gh_1=p_2+\frac{1}{2}\rho v_2^2+\rho gh_2$$

volume of the air cells:

Where v is the flow speed, g is the acceleration due to gravity, h is the hydraulic head, p is the pressure at the chosen point, and ρ is the density of the fluid at all points. Since Bernoulli's equation applies to compressible fluids up to approximately *Mach 0.3*, we start with an

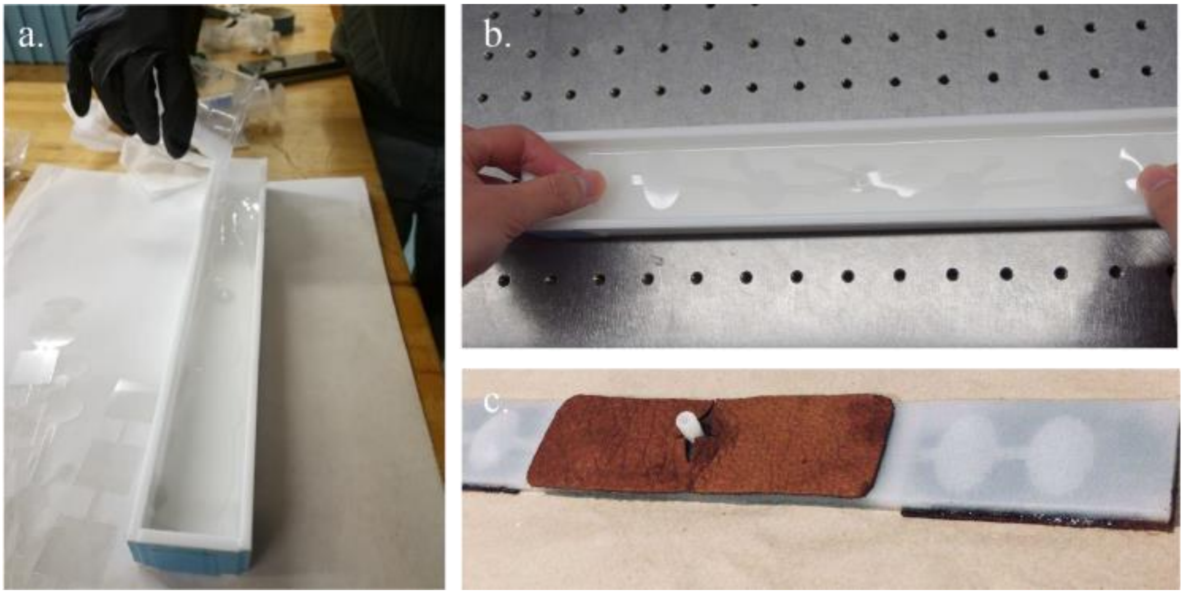

Figure 12. Fabrication process. (a) Laser-cut an acrylic mold and place first layer of silicone elastomer for actuator casting. (b) Place the acetate sheet on top of first layer. (c) Attach leather onto the silicone.

examination of the relationship between the speed of air from the pump and the speed of sound (*Mach 0.3*). The rated pump flow rate is 12 - 15 liters per minute (LPM). We calculate the linear velocity of the flow based on the volumetric flow rate we have with the equation,

$$Q = v \cdot A$$

where Q is the flow rate and A is the surface area. So the flow speed with an air tubing of 4mm inner diameter can be estimated at 15.9 *m/s* ~ 19.8 *m/s*, which is much less than the speed of sound. In such a case, the density of air remains constant, and only the flow rate increases in Bernoulli's equation. We assume that the elevational change is small enough to be neglected, then, as the density of air does not change, its potential energy per unit volume *pgh* also remains the same. The equation can be simplified and we get

$$p_1 + \frac{1}{2}\rho v_1^2 = p_1 + \frac{1}{2}\rho v_2^2$$

After testing the maximum pressure that a 12V DC air pump we use can generate, we get the range of source pressure at 101.325 *kPa* ~ 151.988 *kPa*, which is 1~1.5 *Atmosphere*. Knowing the value range of pressure energy, fluid density, and initial flow speed, we express the target flow speed v_2 as

$$v_2 = \sqrt{\frac{2 \cdot (p_1 - p_2)}{\rho} + v_1^2}$$

and can get an estimated range of v_2 at 15.9 *m/s* ~ 93.0 *m/s*. With the same tubing size, the volumetric flow rate is estimated to range from 200 *ml/s* to 1172 *ml/s*.

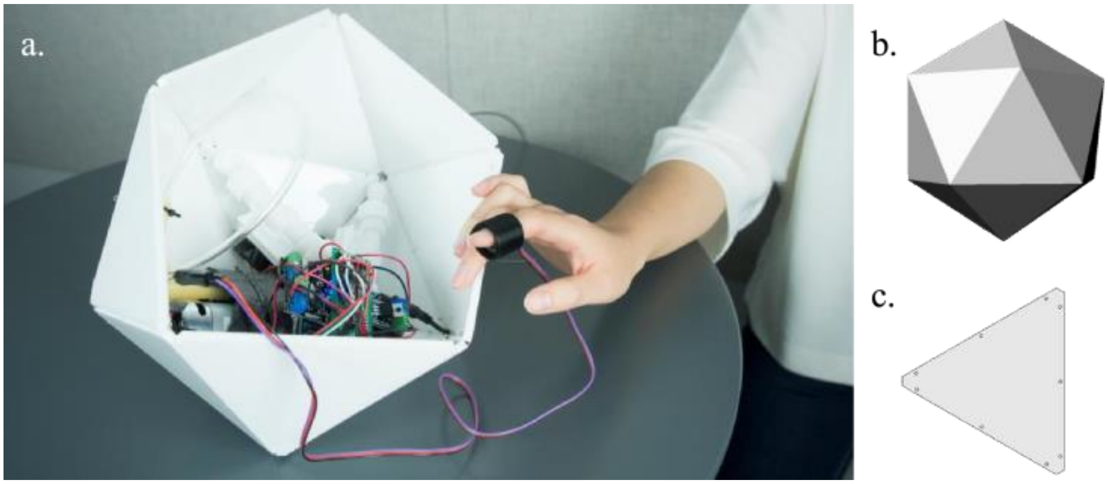

Figure 13. Memorizer structure overview. (a) Memorizer's physical model. (b) Memorizer's digital model. (c) Flat view of one panel of the memorizer.

The air cells of our design have a total flat area of 50 *cm2*, with an expected 2 *cm* height after inflation. The estimated volume of inflated air chambers in total should be less than 100 *ml*, given the shape of these chambers is semi-spherically extruded from the surface. Therefore, even if the pump is running at the minimum flow rate of 200 *ml/s*, our device can still actuate a pulse behavior of up to 120 beats per minute (BPM). Certainly, with a higher value of flow rate, a higher BPM can also be achieved.

4.3.8 Preliminary Results

The BVI system has been introduced and demoed at various conferences and art exhibitions such as International Symposium of Electronic Art (ISEA) 2019, International Workshop on Haptic and Audio Interaction Design (HAID) 2019, and Santa Barbara Center for Art, Science and Technology (SBCAST). We received numerous feedback about the system and the overall experience it provides. Based on our observation during these exhibitions, most of our audience was interested by the design of the choker for its targeting actuating area on a user's neck rather than on the hand or other body parts commonly seen in other haptic devices. The connectivity between two users to viscerally experience each other’s body signals was also favored by many users as they believe it provides a sense of intimacy between each other while not actually having direct body contact. To some degree, our system makes it possible to bridge two people remotely with affective virtual interactions in between. Our system was also easy to set up for a user. The entire process of wearing and placement of our device onto a user’s body, including an HMD, takes less than 15 seconds. The choker we designed for the BVI system is highly bendable and it easily adapts to necks of various sizes. Our design of the antenna component was also well received for its lightness and flexibility that we did not see users having trouble turning or moving during their VR experience when they were wearing the whole system.

During our demonstration of the system, we found that different areas on the neck have different sensitivities to external pressure. After testing different actuating patterns with different positions and sizes of air cells, in our latest design iteration of the choker, we decided to move most of the air cells to the back side of the neck and decreased the size of air cells to maximize the haptic experience of air inflation.

4.3.9 Summary

Our design of a haptic data representation on the neck not only gives the user a sense of touch of the biological state of a person but also produces a deeper intimate situation of sensing others by touching body parts that are not socially accessible. Prior works on haptic data displays were often investigated as ways of information representation, such as position sensing and movement coordinating. They are commonly used for emerging media such as virtual reality (VR), but seldom for affective interpersonal communication. We drew inspiration from psychology and physiology research that touch stimulation can make infants behave more actively with the environment and emit more smiles and vocalizations [135]. It is also proven that touch is often associated with enhanced affect and can convey a stronger sense of bond between people [136]. Therefore, our work can be seen as a continuation of these ideas with a more intimate approach adopting a soft robotic method empowered by virtual reality. Using soft materials that are highly skin-friendly, an effective communication of affect can be achieved. By translating biometric data into haptic stimulation, our device allows users to experience biological events from pulse which is another form of intimate communication. The metaphor here is the stethoscope that is used for auscultation or listening to the internal sounds of the human body. This type of communication potentially can go beyond conventional social interaction and can possibly be an effective method of building effective relationships among people.

4.4 Eccentric Nature (2020)

We are living in a world that is increasingly independent of physical boundaries. The planet we inhabit is evolving into an extensive web of interaction supported by invisible infrastructures of real-time and high-speed communication networks. Our ecological systems, which used to be defined by geographic borders, are now mixing and merging into a singularized global network layer that is controlled by human software. Sociologist and philosopher Benjamin Bratton proposed a theory of “stack”, an abstraction and conceptual map of layered relations between models and reality, between the internet and social structures [16]. He particularly pointed out this idea of the “nomos” of the cloud, a new type of normative standard that is replacing the old standards of the world that used to be defined by the physical borders of sovereignties and cultures, or by the material reality based upon geographies. The "nomos" we are forced to live with nowadays is simply defined by the emergent network of cloud platforms and their providers, in the name of "service" for its "users" — us. While we inhabit search engines, social media, VPN, blockchains, or Tor, the nomos on each platform will never easily resolve itself into any consensual model. The capital behind these platforms will eternally encourage competition and disruption in the open-source communities' efforts of cloud structure building or collaboration in the name of innovation and progression. How can we as globalized citizens and individual participants, be more actively involved within this gigantic networked reality? What kind of new virtual ecology are we capable of creating with different stakeholders of services, network infrastructures, cyberspaces, and other non-human entities remaining on the physical earth?

In this project, I aim to deliver a metaphorical depiction of the complex dynamism and conundrum that exists in our capital-driven network ecology. I design and create different types of virtual critters to symbolically represent the involved entities of our networked reality in a virtual reality environment. At a broader conceptual level, I use agent-based modeling to drive the behaviors of these virtual critters to simulate the interactions between different human and non-human entities, their conflicting interests, desires, and evolving momentums within a fictional economic system. At a user experiential level, I take this simulation-based immersive environment as a way to explore an interactive paradigm for the users by which they are closely connected with many non-human entities and are in dynamic relationships with them. A multi-level and multisensory immersive VR world is then to further turn and encourage the audience to be part of the emergent network. The virtual agents in VR space are designed with genetic algorithms to simulate the evolution of various biological species so that the populations of

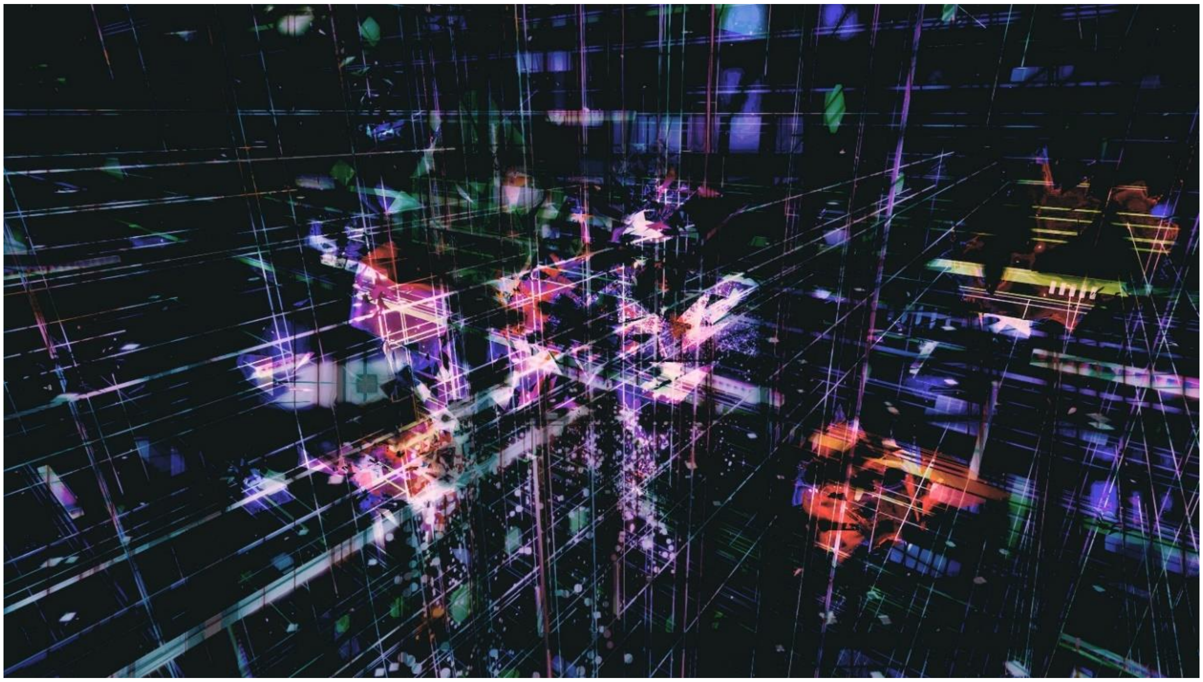

Figure 14. A concept illustration for Eccentric Nature. A virtual space design with connected threads and lines. Interaction and movement in the space can easily affect other entities.

these agents are dynamic and changeable by external factors such as audience intervention. This experience allows the audience to embody themselves in a virtual ecology surrounded by these intelligent agents, migrating from the real world into a virtual one, while reflecting upon the complex nature of our networked reality and their own presence in the network.

4.4.1 Concepts

“Eccentric” comes from the idea of “eccentricity”, which describes a state of movement off from the central axis and implies the tilted, imperfect, and sometimes turbulent geo-political climate that is constantly drawing unpredictable boundaries in our life. A broken form of "eccentricity" denotes a collective state of being eccentric in the public domain, a city of eccentric culture that is deviating from the centripetal governing force, and a speculative future where creative energy is transformed into a counter-force to push the boundary and define new territories.

“Nature”, on the other hand, provides a systemic and ecological New Materialist perspective (as described in Chapter 2.4), questioning and examining the intra-activity among different biological species, artificial objects, emergent machines, and humans. For the sake of better symbiosis, instead of leveraging and exploiting nature with power and desire for consumption, we link ourselves with the entities beyond our perception, converse, and empathize with them in a new sensational network that exists only in virtuality.

4.4.2 Early Prototype

Eccentric Nature comes from my early social simulation experiment *Money, Poetry, Proletariat* [137] in 2018 at the Allosphere Research Facility[7] (see Figure 17). This early prototype is an abstract capitalist production simulation created with a simple agent-based model. Agents in this system are stratified into three different classes - Capitalist, Worker, and Miner - according to their productivity and income level (Figure 15). Agents of each class have their exclusive class behaviors, such as mining, collecting, job hunting, producing, trading, and profiting, and they have to, during most of their lifetime, commit themselves to those behaviors in order to earn capital while surviving in this system. At the same time, all of the agents are programmed with internal desires, changing moods, and basic levels of personality such as patience and sociability, that can indirectly affect their productivity and income.

In *Money, Poetry, Proletariat*, above the autonomous nature of individual agents, a Market System (Figure 16) functioning as an invisible hand is designed to monitor the overall

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[7] https://allosphere.ucsb.edu

economic system of these agents. It calculates the statistics of different aspects of society, such as population ratio, poverty rate, and resource scarcity, and correspondingly determines the monetary policy in real-time on price, tax, and welfare. However, unlike a real-world capitalist scenario, agents are evaluated by two non-exchangeable currencies - *Money* and *Poetry*. Money is the common capital reserve that practically decides the lifespan of the agents, while Poetry disrupts the production routines of agents and generates irregular behaviors outside social "norms". Both of the two capitals can influence the living status of agents, while they are absolutely designed to be unexchangeable, which potentially dematerialized the whole consumption-based social reality into a more complex non-reality.

Eccentric Nature adopted part of this economic model as succession and incorporated similar properties such as desires and moods, as well as behaviors such as mining, collecting, profiting, and trading into the new model. While the early prototype is more of an autonomous system that sustains and evolves by itself to let the audience observe and watch the emergent behaviors coming out of the simulation, this new project takes the audience into the simulation model and permits direct participation from the audience in a virtual reality space. This extra human factor significantly changes how the simulation model is going to perform and generate possible outcomes and makes it difficult to predict what may happen in the next moment during the experience.

4.4.3 Relational Entities

In eccentric nature, there are seven different types of intelligent agents (see Figure 19). These agents are motivated by different goals which they must fulfill to survive in this highly competitive environment. At the same time, their inherent states such as energy cycles and

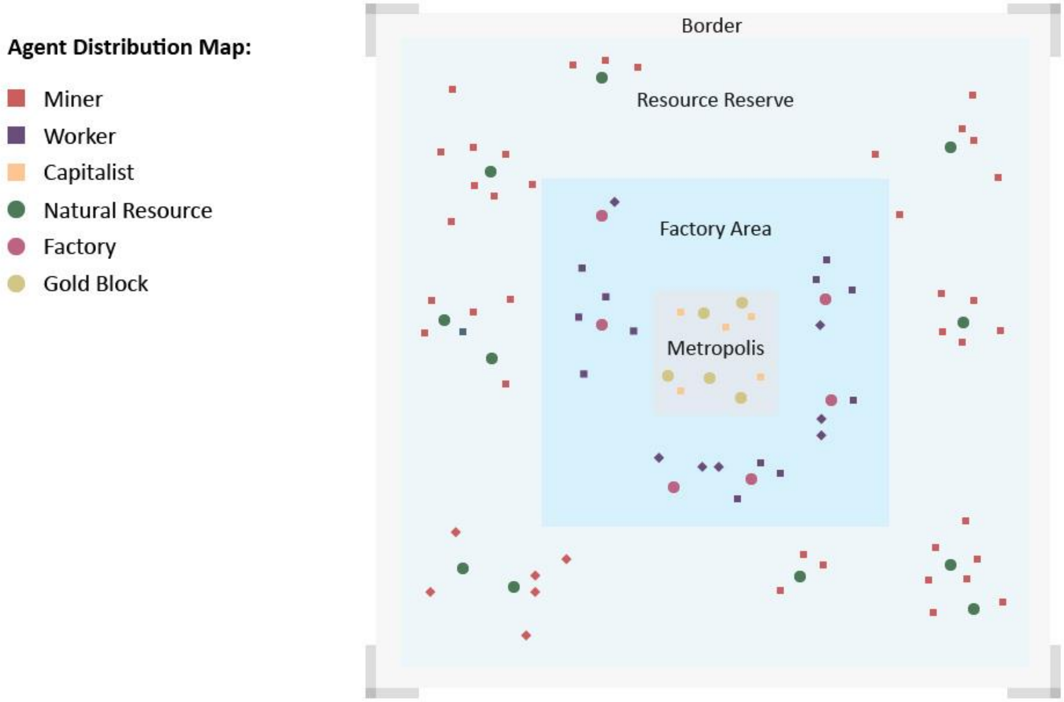

Figure 15. An overview of the spatial distribution of different classes and resources in Money Poetry, Proletariat.

collection desires determine their strategies of navigation and resource-finding in the virtual space. The human participant is considered a special type of agent who can also get involved in this virtual ecology. Interactions performed by a human participant can affect the movements and inherent states of some agents, thus causing changes to the population distribution of certain agent species. Figure 18 shows a relational map that delineates the basic relationships between each agent species.

Planktons - Planktons are the basic material-like static agents that are seen as the most desired resources by other agents. They do not have the capacity to actively move around in space but they generate profitable resource blocks that are necessary for other agents to collect and trade. There are often a fixed number of planktons, and each plankton has a random number of collectible resource blocks. Different agents can come by plankton to take these resource blocks and each plankton has its own regeneration rate of resource. Larger agents often have a faster collection rate than a plankton's regeneration speed. Therefore, when a plankton may be exhausted at a certain point and eventually die because of over-collection.

Schoolers - Schoolers is the smallest as well as the most common active agents that populate almost everywhere in eccentric nature. They constantly flock around with each other randomly in the space with the hope to find planktons. Once they find a plankton, they will stay with it to collect the resource blocks until they have a full load. Then they will take these resource blocks to the largest agent, Castle, to trade for energy so that they can continue to move and loop through the collection process again. If they fail to complete the collection or deliver the resource blocks in exchange for energy, they will die and disappear.

Captivators - Captivators are larger predator-like agents. They have slow movement but are sensitive to the environment in finding schoolers. Unlike schoolers that must collect resource blocks from planktons and trade for energy, captivators can directly acquire energy from both planktons and schoolers. They simply try to follow schoolers nearby, slowly absorb energy from them and let schoolers lead them to where the closest planktons are. Then very quickly they can exhaust a plankton and convert all the resource blocks in it into their own energy.

Tadpoles - Tadpoles are agents that help recover planktons. They do not directly generate resource blocks of planktons but their presence nearby a plankton can increase its resource regeneration rate. Tadpoles are highly active and they will surround the human participant if they encounter any. They may follow the participant for a long time until their energy level is

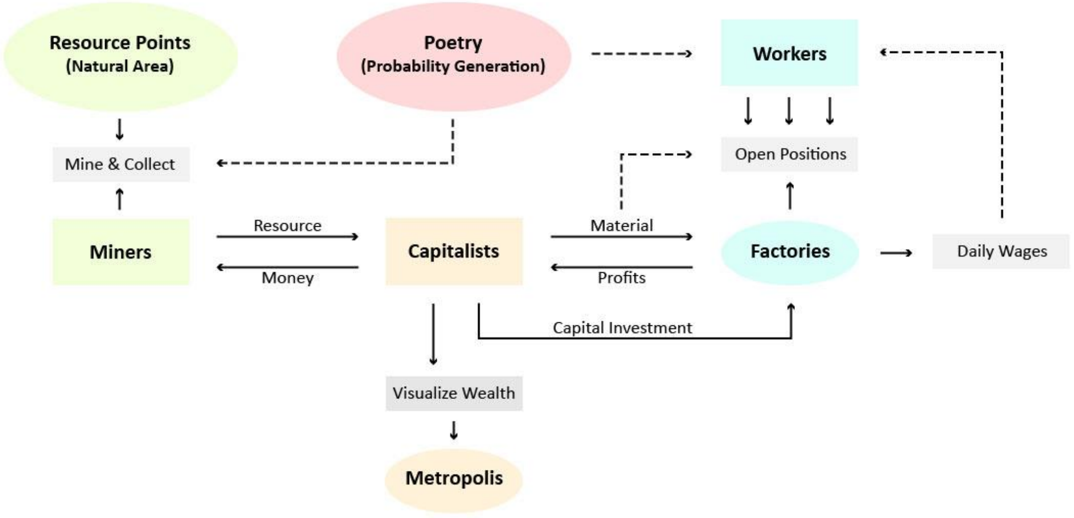

Figure 16. A system diagram of Money Poetry and Proletariat illustrating the interactions between different classes and high-level objects

low. Tadpoles' energy level is not dependent on external resources but can recover by going into sleep mode for a short period of time.

Castles - Castles are the largest agents in eccentric nature. They are gigantic structures slowly moving around. Castles do not produce or predate on any other agents but they collect resource blocks from schoolers and provide energy to them in return. When castles have collected a large number of resources, their bodies expand and grow extra layers. They are simply immortal and dominate the entire virtual space.

Spirits - Spirits are portal agents only interacting with human participants. They appear at random places often when a large number of agents are aggregating together. Whenever a human participant encounters a spirit, they will be teleported to other areas of the virtual environment. In this way, a participant won't stay too long in one place and their impact in the space can be more evenly distributed.

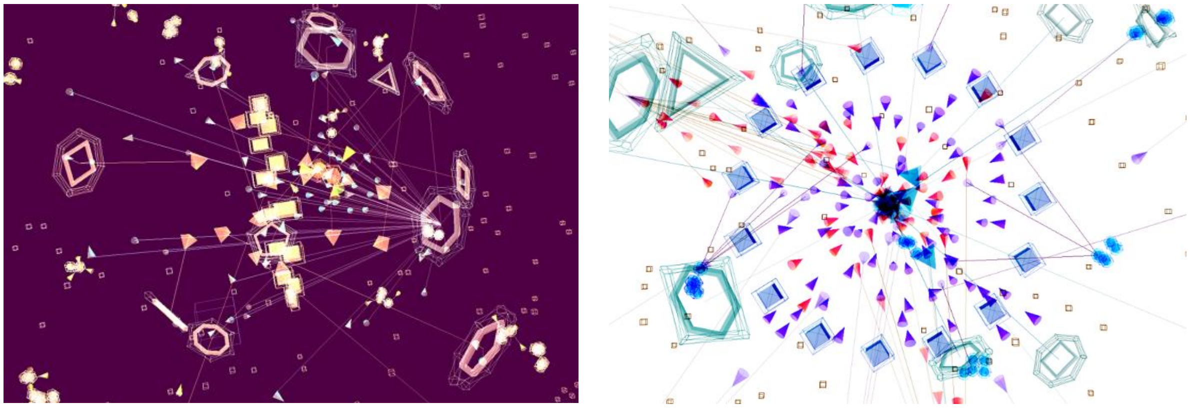

Figure 17. Selected simulation moments from Money, Poetry, Proletariat

Mists - Mists are the last type and the most mysterious agents. They do not participate in the virtual ecology at the early stages. They only appear when a plankton has been devoured permanently by a captivator. A mist is made of beautiful shapes and is visually stunning to see but it does not do anything to help maintain the species diversity in the virtual ecology.

4.4.4 Participant Choices

Human participants can engage with this virtual ecology by interacting with schoolers, tadpoles, and captivators. As captivators' devour of planktons is irreversible, the participant can actively guide schoolers to move away from captivators to keep the balance of the populations of different species. In some cases, the participant may also attract tadpoles to stay nearby planktons to help the resource regeneration to prevent exhaustion. On the other hand, participants can also choose to help captivators devour planktons, or simply stand by as an outsider. Although this may lower the diversity of species in the virtual environment, the result of all planktons being devoured is simply a space full of mists, another possible reordering of virtual ecology.

4.4.4 Implementation

This system was built in the Unity game engine. As there is a huge number of agents (about 6000 ~ 8000 units) of complex behaviors flocking at the same time in the virtual space, GPU-based compute shaders were used to accelerate the parallel computation of the energy states and movement of all the agents. A single archetype of common properties and functions was designed to program the behaviors of all the agents. That is, every agent has the same properties but they are initialized with different parameters based on their species. The main properties and functions are:

- Sensing radius - it determines how far they can find their primary target. Agents of smaller sizes tend to have shorter sensing radius.
- Primary target - all agents have a goal to reach, but this goal can change based on their status and energy level.
- Secondary target - it is used as an alternative goal to replace the primary target in certain situations. Mainly used for interaction with human participants so that the agents can be attracted and navigate to participant-designated areas.
- Energy function - each type of agent has its own energy computation function based on time, travel distance, resources needed, and other agents nearby.
- Navigation function - some agents are more socially aware of their environments and some are not. This function determines how they move and navigate toward the target destination.
- Activity desire - the desire of an agent determines how active they are, and has an impact on their speed of movement. The level of desire is probabilistic and resets to a new value at a certain frequency.

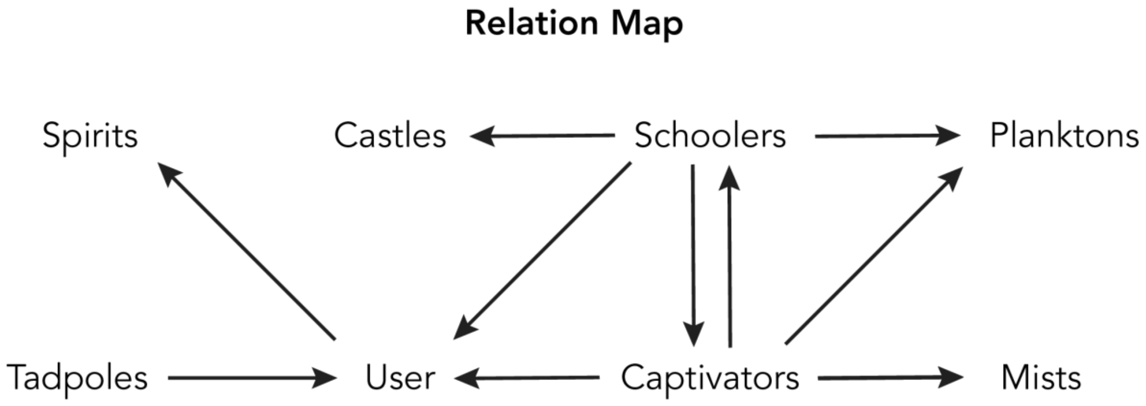

Figure 18. A relation map for Eccentric Nature indicating all the possible interactions between different agent species.

4.4.6 Preliminary Results

Eccentric Nature was exhibited at CultureHub LA's Refest 2019 [138] and Currents New Media Festival 2020 [139] (see Figure 20). Based on general observation during the exhibitions, I found most of the audience was interested in the possibility of interacting with different agents. The various types of agents have certainly increased the audience's desire to engage with the virtual environment and to spend more time exploring and discovering different aspects of the experience. More importantly, when the audience realized that their choices of interaction may have a significant impact on the development of the virtual ecological system, they often became more serious and careful about the way they behave and interact, with a hope that they can "sculpt" the virtual reality into a space matching their intention.

4.4.7 Summary

This project is an investigation of using agent-based modeling to deliver a relational activity in virtual reality where human participants can deeply engage in a virtual ecology and change the overall behaviors and living status of many different agents. Iterating from an early prototype that simulates the relationships only between autonomous agents, this work now also includes human participants in the simulation. Any decision or choice made by the participant can easily cause permanent and sometimes irreversible consequences in the virtual environment. Therefore, the tension between the participants and the virtual agents can be observed during their immersion into the virtual space. All the agents I designed are metaphors for different entities in the real world, corporations, capitalists, network infrastructures, etc. Certainly, the real world is much more complex than a simulation, but incorporating relationships, especially those non-reconcilable ones, into a virtual reality narrative can possibly make the audience peek into a particular aspect of our reality and see the world differently by their simulated direct engagement.

4.5 Conclusion

In any type of reality, there is always a need for social relationships. Virtual environments we encounter these days often come with high-quality visual graphics and spatialized soundscapes, but the virtual elements in these spaces are often “distant” from us even though they are presented right in front of us. This feeling of social distance is very much like the moment when we see other people’s faces on a computer screen during a video call, an excitement that comes from a sense of as-if-in-person along with the disappointment of being physically separated. The major cause for such a mixed feeling is understandable, as the modalities of communication (e.g., visual and auditory) are not yet sufficient enough for us to think that we are “over there” with another person. The projects discussed in this chapter aim to look at how we can surpass this limit by incorporating more participatory forms of

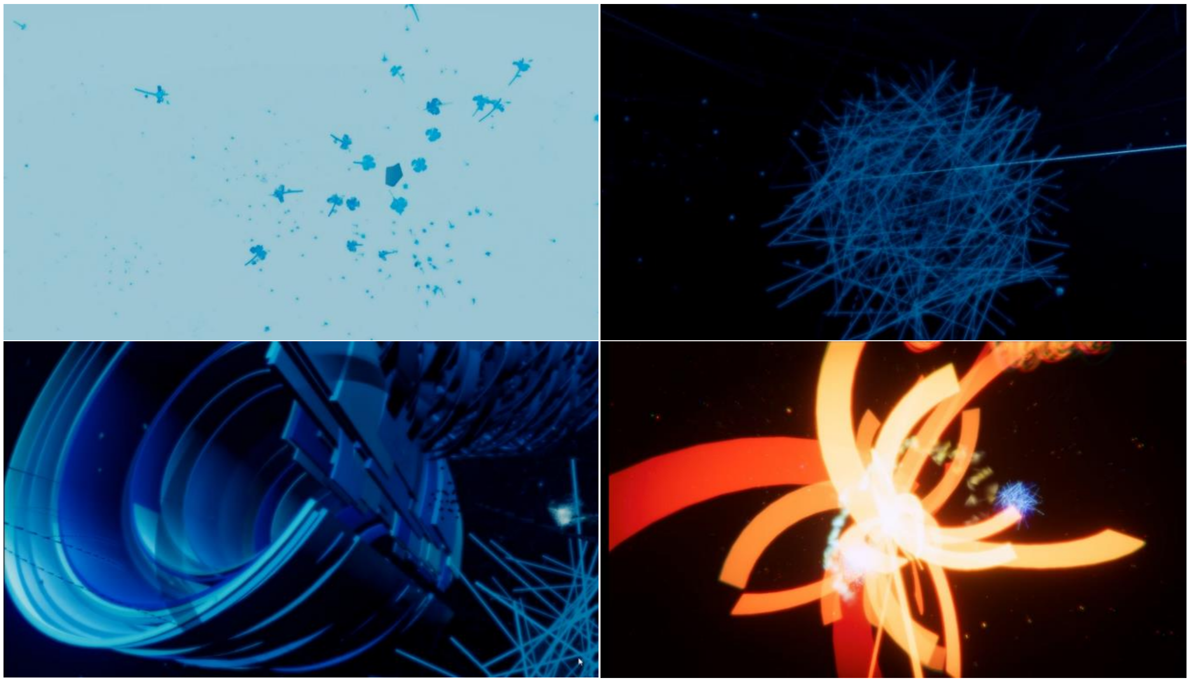

Figure 19. Visual design of different agent species in Eccentric Nature. Top left: schoolers that constantly flock around with each other in the space. Top right: a captivator of morphing structure that can absorb small agents like schoolers. Bottom left: a castle that slowly and autonomously move around to serve as a shelter for many small agents. Bottom right: a mist that only appears when the population of schoolers has been decreased.

interaction that may strengthen our relationships in an immersive environment. By providing relational possibilities that one can develop with other human and non-human entities, I try to complement the participant's sense of immersion and social co-presence.

The two art experiments demonstrated different ways and techniques of how we can design and develop relational interactive experiences. Biometric Visceral Interface explores face-to-face intimate relationships by which one can remotely connect and feel the presence of each other. The effect of virtual avatar embodiment and haptic feedback also transforms the participant's perception and expectation about the virtual space into a private social space inclusive only to their remote partners. Eccentric Nature looks at a broader fictional and metaphorical space of broader social relationships that are not centered around human beings

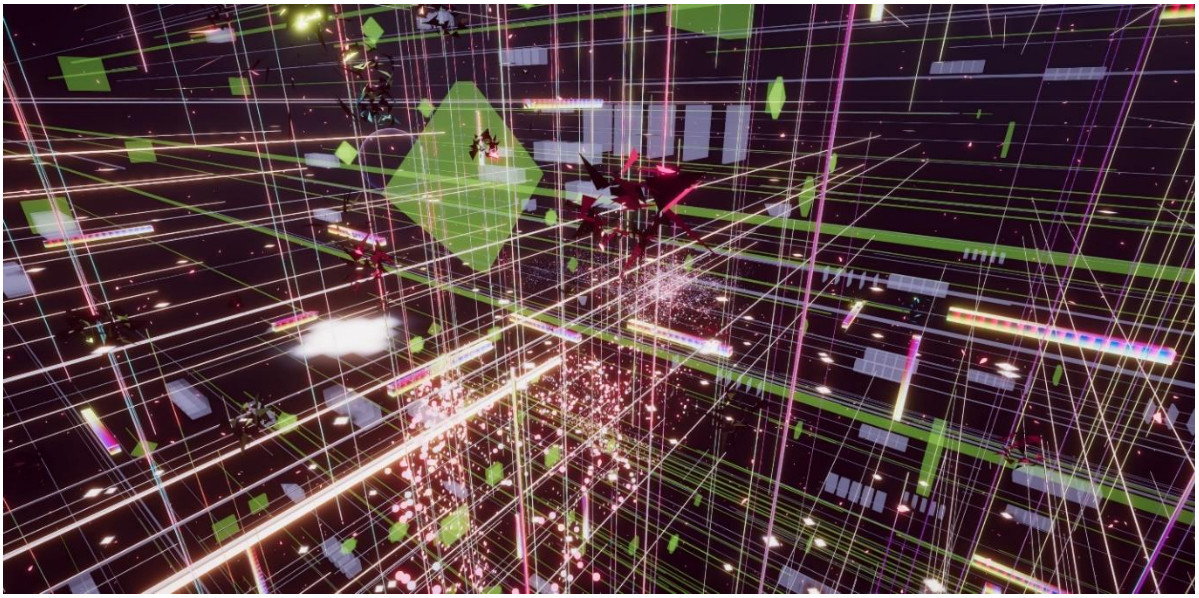

Figure 20. Selected display image of Eccentric Nature at Currents New Media Festival 2020.

but are based upon a complex network of abstract and autonomous entities. Participants during their interactions with virtual agents become the activators and contributors of a virtual ecology, no matter whether they are conscious or unconscious of their behavior impact. Both two works allow them to immerse into a virtual reality with relationships that are difficult to experience in physical reality. These experiments also suggest a new design space unique to the virtual domain, which may conceptually challenge the participant’s expectations and understanding of their relationships with many different things around them.

5. RELATIONAL STORYTELLING

Relational immersive experience design well supports interactive storytelling. As discussed in Chapter 3, a relationship is essentially an abstraction and manifestation of the interactions between two entities. The outcomes and phenomenon of interactive behaviors are how human participant understands and recognizes the nature of the reality in front of them. A relation contains not just the past events that have happened, but also the competence of the entities, and their momentum to move and act upon each other in the near future. This revelation of competence is at the core of interactive storytelling. Unlike conventional storytelling where the actions of characters and the happenings of events are arbitrarily determined by the author, interactive storytelling assumes the human participant's responsibility in activating the performance of virtual agents and objects. This activation requires the participant's knowledge of the agent's competence, and a sense of feedforward to estimate the possible outcome before an action is taken by the human participant. Relationships in a story provide such a sense of feedforward as a narrative guide that one can follow to make interaction choices, although relationships are never constant and are largely dependent on the performance history of virtual entities. They are subject to change as the story moves forward.

In this chapter, I present two authoring systems that enable new types of storytelling by introducing new relations. SceneAR is a smartphone application for the easy creation of sequential scene-based micro-narratives in AR[8]. What makes this authoring app unique and novel is its capacity to let one person create and design an initial story scene sequence and then have another person remix and continue developing the storyline based on the initial narrative setup. Beginning from the same story scene sequence, multiple possible outcomes can be developed by different creators, while the creators may also formulate an invisible collaborative relationship during the co-authoring process. EntangleVR is an interactive VR scene creation system using the concept of quantum entanglement[9]. It specifically explores the possibility of using entanglement to describe the interactive relationship between multiple states of virtual objects and human participants' interaction choices. Both of the authoring platforms target users with zero-programming knowledge and are easy to learn and use.

5.1 Introductions

Short-form digital storytelling has become a popular medium for millions of people to express themselves. Traditionally, this medium uses primarily 2D media such as texts (e.g., memes), images (e.g., Instagram), GIFs (e.g., Giphy), and videos (e.g., TikTok, Snapchat). While modern smartphones are well capable of AR features and 3D content rendering, AR storytelling isn't yet widely available to the consumer market. One of the main challenges in delivering AR-based short-form stories is the lack of authoring tools to support easy editing and creation of AR content. Existing authoring methods often require cross-platform environments and inter-operation between different software. As we foresee the need for a social media space of AR storytelling, an authoring tool that allows users to create, share,

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[8] SceneAR presented in this chapter is based on the paper [422]. This work is co-authored and supervised by Professor Andrés Monroy-Hernández and Professor Misha Sra.

[9] EntangleVR in this chapter is based on the paper [423], co-authored and supervised by Professor Marko Peljhan and Professor Misha Sra.

consume and remix AR content all at once just like existing methods for 2D media is needed. My research investigates how we can expand the modalities of storytelling from 2D to 3D, and bring new creative opportunities to let anyone be able to create and share immersive narrative experiences. I am particularly interested in lowering the technical barrier to creating such immersive experiences by providing easy-to-use interfaces and easy-to-learn workflows.

On the other hand, existing authoring tools for AR and VR stories often focus on only the visual and auditory aspects, with very limited support for designing interactions between virtual objects and the audience. Incorporating interactions into a story can make an experience more expressive and engaging to the story consumer. Especially when the audience's choice of interaction can lead to a direct impact on the story, it will provide them with a stronger sense of plausibility in the virtual environment. However, designing a story where the plot can be influenced by audience interaction is a challenging task. Different from designing for a single linear narrative structure, It requires a tremendous amount of effort to create multiple storylines that can be activated by different interactions. To overcome this labored effort, we need to find out a new computational method and interface that can accommodate multiple story outcomes and interaction possibilities so that the creators won't find difficulty in designing this type of story. My work EntangleVR investigates how quantum computing may support the authoring of complex interactive narratives by introducing the idea of entanglement. I introduce unique features from quantum computing to storytellers and investigate how we can better support the creative process of interactive VR scene composition.

5.2 Related Work

5.2.1 AR Storytelling

Prior work has explored AR for a variety of use cases like education [140], creativity [141], museum exhibits [142], animation [143], location-based experiences [144, 145], tourism/heritage [146], collaboration [147], journalism [148], and audio-only experiences [149]. While there is an abundance of research on how to use AR, to our knowledge, a general purpose AR app for everyday use that allows users to create, share, and remix short-form narratives has not yet been explored. Early works look at augmented print media that uses AR interfaces like MagicBook [150] and edutainment [151]. Magic Story Cube [152] introduced a tangible AR interface in the form of a folded paper cube where each unfolding produced different pieces of a story with non-animated visuals, voice, sound and music. ARFacade [153] presented an interactive AR drama enabled by conversations with the characters. More recently, Kljun et al. [154] explored the design space of AR-augmented comic books and examined how digital content can influence the behaviors of child readers. Wonderscope [155] introduced an interactive storybook app for kids with integrated voice recognition to encourage reading. StoryMakAR [156] is a recently introduced system that merges electro-mechanical devices and virtual characters that allow users to create stories with a browser-based block programming interface. MARAT [157] is an mobile authoring application that works with a back end tool that museums can use to design virtual exhibits. Of these prior works, both StoryMakAR and MARAT allow users to author AR content, though only the former allows the creation of a story using one of four virtual characters available in the app and custom hardware. Almost all other projects provide AR content already created by experts for consumption by non-experts. In my work, I introduce SceneAR, an app that everyday users can use to create, view, share, and remix scene-based micro narratives with smartphone-based AR.

5.2.2 AR Authoring

Prior work in AR authoring can be classified into two main types: low-level approaches that provide toolkits, libraries, or frameworks like ARToolkit, Studierstube, or Vuforia [158, 159, 160] and high-level approaches that are desktop-based authoring environments like Lens Studio, MARS, SparkAR, DART, or ComposAR [161, 162, 163, 164, 165, 166]. More recently, a third approach has become feasible with improvements in tracking and registration technologies, supporting AR content creation and consumption within the same AR system [167, 168]. Feiner et al. [169] developed one of the earliest mobile AR computing systems to allow spatially registered information for both indoor and outdoor locations to be accessed and managed by users through a combination of a see-through, head-worn display and a hand-held pen-based computer. Guven et al. [170] proposed the Freeze-Frame technique that enables the user to capture a snapshot of the environment and author AR content directly on top of it. Hengel et al. [171] presented a form of in situ authoring where 3D models generated from images could be inserted into the video stream. Langlotz et al. [172] presented an on-site authoring system that allows users to add 2D drawings and simple 3D objects in AR, though they do not offer any ability to scale, rotate, or move the virtual objects. Location-based game Tidy City [173] allows end users to record and upload images and GPS locations to create AR scavenger hunt missions for other players. Zhu et al. [174] proposed a bi-directional authoring tool that allows desktop users as well as maintenance technicians to author content on-site. Both of these approaches are similar in that they utilize pre-created AR environments that users can modify in a limited manner by taking new images or adding new text. None of these in situ authoring systems are real-time or immersive, namely, they do not allow for “developing and experiencing the content concurrently throughout the creation process” [175]. In contrast, SceneAR is an immersive and in situ authoring tool that enables non-experts to create and experience AR scene-based narratives in a smartphone AR app. By providing access to thousands of 3D models, SceneAR makes authoring simpler and faster, much like Snapchat allows users to add AR lenses to their faces without having to create each lens from scratch.

5.2.3 VR Scene Authoring

VR scene authoring tools allow users to create a virtual environment by adding and manipulating virtual objects as well as their behaviors. Prior works have looked at various forms of VR scene authoring and prototyping. We classify two main types: low level and high level approaches. Low level approaches provide programming libraries or frameworks to help build VR applications such as Alice [176], CalVR [177], FreeVR [178] or VRPN [179]. High level approaches are rapid prototyping tools mainly designed for spatial scene creation, 3D user interface, and object interactions that are independent from hardware architecture, operating system or VR device configuration. Steed et al. [180] proposed a visualized data flow representation for defining behaviors in a virtual environment. VR Juggler [181] and RUIS [182] are frameworks that let users easily build VR applications without necessary technical knowledge regarding the underlying hardware devices. Billinghurst presented 3D Palette [183], a new interface for rapid 3D virtual scene creation using tablet input, 6DoF direct input and multi-modal input. More recently, immersive authoring tools are becoming more available by the concept of What-You-eXperience-Is-What-You-Get (WYXIWYG) [98].

ISAAC [184] is one of the earliest authoring tools to support interactive construction of virtual worlds directly in an immersive setup. 360proto [185] allows users to rapidly create AR/VR prototypes from paper and have direct access to the device view during the editing process. FlowMatic [186] proposed a reactive visual programming tool to program and create interactive scenes in VR. Taking inspirations from both high level approaches and immersive authoring, I propose a hybrid approach of scene authoring in the EntangleVR system by providing a 2D visual programming interface for rapid prototyping while allowing an instant and interactive preview of created VR scenes without compiling or building.

5.2.4 Quantum Computing for Creativity and Learning

The quantum phenomenon and concepts have also been widely gamified and the creative community has gained rich inspiration from quantum science. Quantum Moves [187] is an online platform gamifying optimization problems in quantum physics where players move simulated quantum atoms to create optimal control solutions for real atoms. Hamido et al. [188] proposed a quantum computing based music synthesizer that maps quantum circuits into music scores. Quantum Game with Photons 2 [189] is an online drag and drop puzzle game that visualizes the photons as light waves with forms drawn from quantum equations. Anupam et al. [190] presented a digital game design process and case study for classrooms which involves and supplements introductory quantum mechanics curricula. Other educational tools to teach the basics of quantum computing have emerged in formats such as board games [191] and 3D puzzles [192]. Recent work by Zable et al. [193] investigates using VR as an educational tool for quantum computing, allowing users to interact with a 3D Bloch sphere visualization of a qubit. EntangleVR not only looks at how quantum computing and its related concepts can

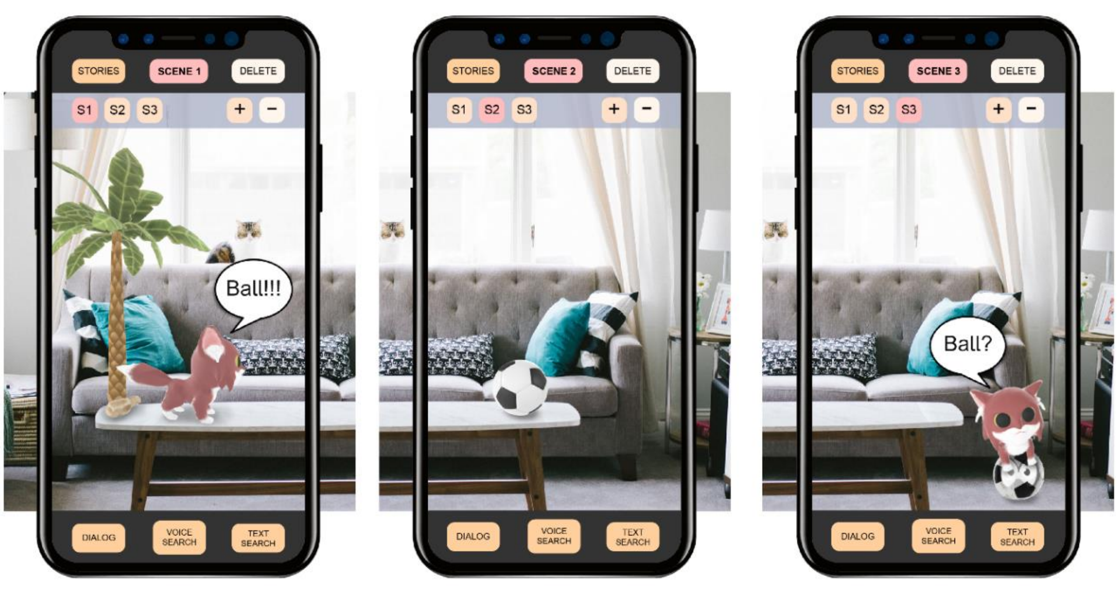


Figure 21. Concept design of a micro story told in three scenes where the user can view each scene on surfaces in their environment as a sequential 3D comic--like story made of three panels of 3D objects and dialog balloons.

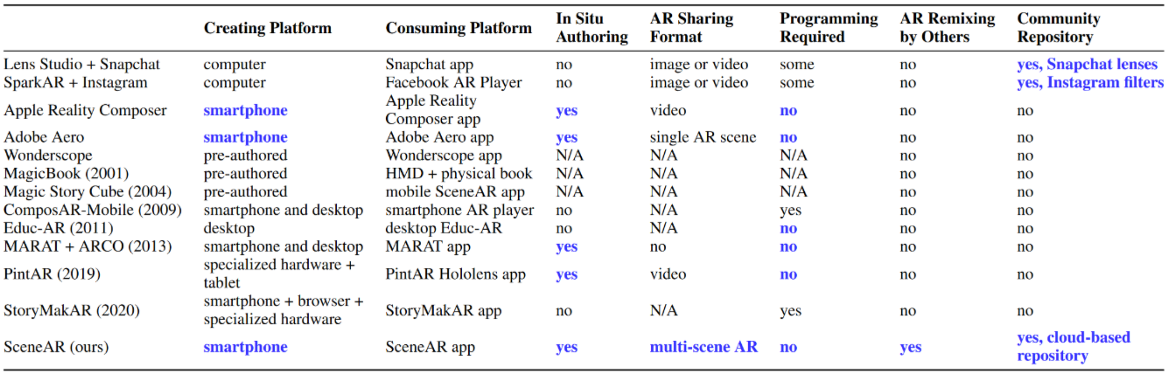
benefit content creators in VR, but also aims to help its users learn new computational thinking concepts from the quantum domain through encapsulation of concepts in the visual interface.

5.3 SceneAR (2021)

Examples of early forms of storytelling with sequences of pictures can be found in Egyptian hieroglyphs, limestone carvings of Buddha, Greek friezes, Japanese scrolls, and illustrated Christian manuscripts, to name a few [194]. Over time, using picture panels and text for storytelling evolved into comics. More recently, with digital tools, everyday people can tell their stories through not only pictures and text but also sound and video (e.g., micro stories told with memes, GIFs, Snapchat lenses, TikTok videos etc.). SceneAR adds to this list of storytelling media by enabling the creation and consumption of micro narratives using smartphone-based augmented reality (AR). Unlike popular 2D media, creating micro narratives with AR and viewing them in the physical environment is an under-explored area and presents a rich set of research opportunities as well as unique challenges.

Although AR technologies have become more broadly available, tools for novices to quickly and easily create shareable narratives in AR are fairly limited. Mainstream development tools for creating AR experiences, such as Unity and A-Frame, often require extensive technical skills and programming knowledge [74]. The complexity of tackling AR-specific issues, such as surface detection, object registration, and tracking, can hold creators back despite help from ARCore [195] and ARKit [196] SDKs. Integrated solutions like Spark AR Studio by Facebook [165] or Lens Studio by Snap Inc. [161] are not as complex as Unity, but they are limited to desktop computers, require the use of additional 3D software tools (e.g., Maya and Blender) for creating 3D models, and expect the user to be familiar with programming. On the other hand, apps like Apple's Reality Composer [168] and Adobe Aero [167] have simplified the AR creation process for novices with the added ability to share an AR scene. But even these apps do not support creating or stitching together sequences of AR scenes nor do they allow remixing of AR content.

In this work, we present SceneAR, a smartphone-based application that allows people to easily and quickly create and share micro narratives in AR. The stories are composed of sequences of AR scenes that contain 3D objects and text to form something like an AR comic strip. Although most mobile AR apps **compress 3D space into 2D** for sharing (i.e., turning an AR scene into an image or video), SceneAR enables viewing of the AR scene sequences by placing them in any physical environment (Figure 21). Users can freely explore the 3D models (characters, objects) in the scenes from any angle or distance by moving around and can interact with them using select, rotate, move, and zoom options. Furthermore, unlike existing



	Creating Platform	Consuming Platform	In Situ Authoring	AR Sharing Format	Programming Required	AR Remixing by Others	Community Repository
Lens Studio + Snapchat	computer	Snapchat app	no	image or video	some	no	**yes, Snapchat lenses**
SparkAR + Instagram	computer	Facebook AR Player	no	image or video	some	no	**yes, Instagram filters**
Apple Reality Composer	**smartphone**	Apple Reality Composer app	**yes**	video	**no**	no	no
Adobe Aero	**smartphone**	Adobe Aero app	**yes**	single AR scene	**no**	no	no
Wonderscope	pre-authored	Wonderscope app	N/A	N/A	N/A	no	no
MagicBook (2001)	pre-authored	HMD + physical book	N/A	N/A	N/A	no	no
Magic Story Cube (2004)	pre-authored	mobile SceneAR app	N/A	N/A	N/A	no	no
ComposAR-Mobile (2009)	smartphone and desktop	smartphone AR player	no	N/A	yes	no	no
Educ-AR (2011)	desktop	desktop Educ-AR	no	N/A	**no**	no	no
MARAT + ARCO (2013)	smartphone and desktop	MARAT app	**yes**	no	**no**	no	no
PintAR (2019)	specialized hardware + tablet	PintAR Hololens app	**yes**	video	**no**	no	no
StoryMakAR (2020)	smartphone + browser + specialized hardware	StoryMakAR app	no	N/A	yes	no	no
SceneAR (ours)	**smartphone**	SceneAR app	**yes**	**multi-scene AR**	**no**	**yes**	**yes, cloud-based repository**

Figure 22. A summary of consumer applications and prior research focused on AR storytelling, both pre-authored and user created. The table shows how SceneAR differs from existing work in its ability to allow sharing sequences of AR scenes as micro narratives and its ability to remix shared AR stories.

AR apps, users can also modify and remix [197] AR scenes or entire narratives and share the updated versions. Remixing is defined as the "*reworking and combination of existing creative artifacts, usually in the form of music, video, and other interactive media*" [198]. Figure 22 presents a summary of how SceneAR compares with existing AR apps and prior research that supports some form of story creation and consumption.

As a smartphone-based AR application, SceneAR not only enables "immersive authoring" [175], namely, the creation process that occurs in an immersive AR environment, but also in situ authoring [171], namely, creation that happens in the same app used for consuming the content. We envision SceneAR could be used in areas such as storyboarding, stage design, social media, education, parent-children interactions, and creative arts.

The main contributions of this work are:

- A smartphone-based app that enables non-expert users to easily create, share, consume, and remix scene-based micro narratives in AR.

- A new *Micro AR* packaging format that integrates AR scene layout and content into a single shareable form.
- Three themes derived from analysis of three-day user experience of SceneAR on creativity, spatial interaction, and remixing.
- Six design strategies for designers and practitioners exploring AR for new forms of narratives.

5.3.1 System Design

We built SceneAR in Unity as a mobile Android application using Google's ARCore API [195]. ARCore allows SceneAR to track the position of the phone in physical space and build an understanding of the user's surroundings by detecting planar surfaces in the environment.

Figure 23 shows an overview of the SceneAR system.

5.3.1.1 Narrative Components

Scenes - A micro narrative in SceneAR is defined as a collection of AR scenes, each composed of 3D models that the creator or viewer can place on surfaces in their physical environment. Each scene is modified individually, and users can select, add, or delete scenes as needed with no limitation on the number of scenes in a narrative. Inspired by comic strips, our scene-based design enables a sequential narrative in AR.

Interaction - Interaction with SceneAR has two elements: touch and speech. Touch-based interaction is used for AR object manipulation and for interaction with the app UI. SceneAR recognizes the following touch gestures: 1) tap for object placement and selection, 2) drag for object translation, 3) twist for object rotation, 4) pinch for object scaling, and 5) two-finger

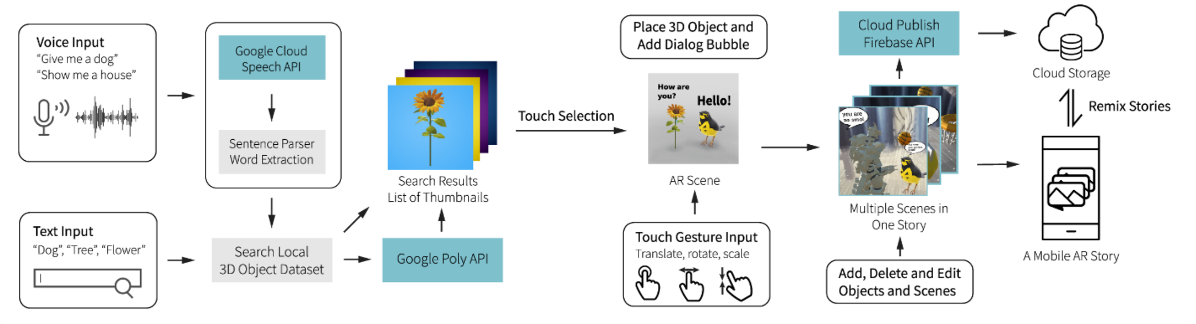


Figure 23. Overview of the SceneAR system (from left to right). Users search for 3D objects to add to an AR scene along with dialog bubbles. Multiple scenes create a sequential story. Published stories are downloaded and viewed in AR. Anyone can remix any story by adding or removing 3D objects, scenes, and dialog bubbles.

drag for object elevation. Speech-based input is used for 3D object search and for creating dialogues as an alternative to text-based search and dialog creation.

Authoring and Presentation - Users have access to a large set of 3D models in the SceneAR app through the Google Poly 3D object library [199]. These objects can be accessed via voice or text search (Figure 23). We included speech input because users are already familiar with using Siri or the Google Assistant to interact with their smartphones. Google Cloud Speech API parses speech data to text, which is then used to return a set of 3D models from Google Poly (Figure 24). The app also includes a smaller set of animated humanoid models to allow creation of scenes if the user is temporarily offline. Figure 24 shows the main steps for creating an AR scene. There is a separate module to add dialog balloons to any object in a scene. The user can choose from pre-existing dialogue or create their own using speech or text. The dialog balloons can be removed or edited for remixing.

5.3.1.2 Application Elements

Publishing, Viewing, and Remixing a Story

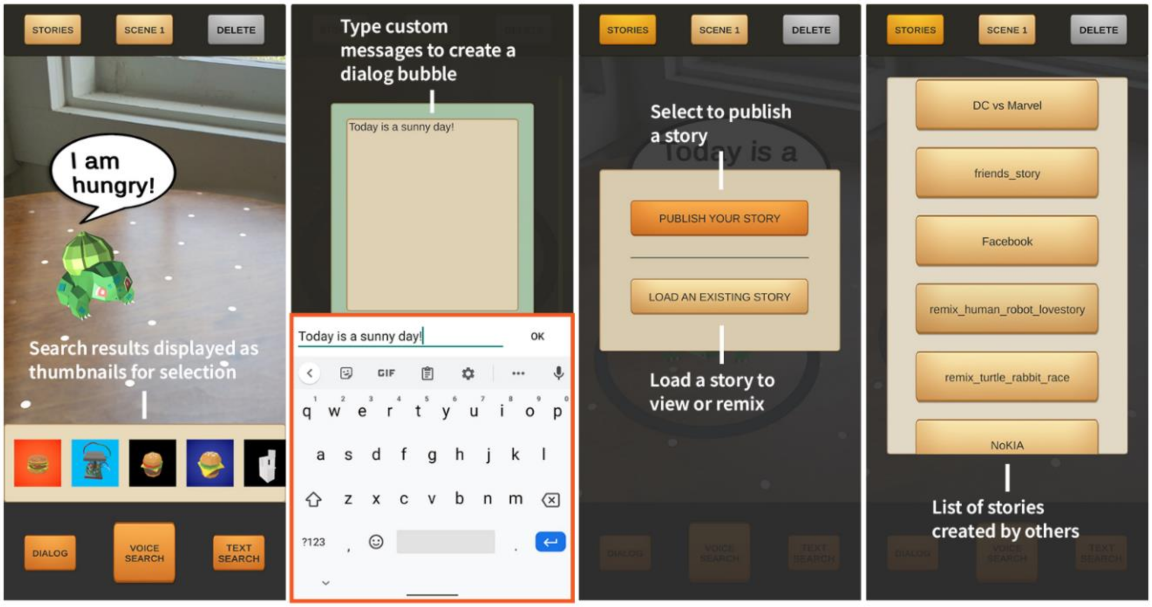
Before publishing (Figure 23), users are asked for a title and a description, including any physical requirements (e.g., best placed on the bathtub) that potential story viewers, who can freely place the scenes anywhere in their environment, should know. Once a scene is placed, the viewer can edit it directly by adding/deleting 3D objects, dialog balloons, or entire scenes to modify or expand upon the narrative. This modified or remixed story can be published with a new title and description.

Micro Narrative Packaging

SceneAR allows publishing and sharing 3D comic-style stories. To enable this, we created *Micro AR*, a new container format for packaging scene-based AR stories. Inspired by the open-source OpenDocument Format (ODF) that packages a text document from different components like metadata, content, and formatting [200], the *Micro AR* format is designed to package three main components of the AR story: 1) metadata, 2) story content, and 3) spatial layout.

Metadata - The Micro AR format contains app-generated and user-created metadata about the AR story. It includes fields such as creator, title, description/viewing guidance, original creator, creation timestamp, and viewing statistics. The metadata defines and differentiates each AR comic as a unique document. Metadata allows the user to browse through a large library of stories before deciding which one to load and view.

Content - Content contains both local and remote data related to each story. Local data are mainly dialog texts created for each scene in a story. These are small in size and packaged for sharing directly. Remote data are content-specific metadata that include 3D asset names and unique keys. Because these assets are large in size, the app uses keys to retrieve the actual 3D



Search results displayed as thumbnails for selection

Type custom messages to create a dialog bubble

Today is a sunny day!

Select to publish a story

Load a story to view or remix

List of stories created by others

Figure 24. Figure showing the main SceneAR scene-creation elements. From left to right: 3D object search results displayed as a scrollable list of preview icons at the bottom. A custom dialog can be added via typing or speech-to-text input. Stories can be published or loaded for viewing/remixing. Browsable list of all stories is available for viewing and/or remixing.

models from cloud storage when needed. The assets are downloaded in the background as the user scans their environment to make the story appear immediately upon plane detection and selection for an improved user experience.

Spatial Layout - All content in an AR story is placed on a physical surface for creating and for viewing. Thus, the Micro AR package needs to track the user-defined spatial layouts in each scene of a story. Positions, rotations, scales, and groupings of 3D objects relative to each other in each scene are recorded and packaged so that each reconstruction and viewing of an AR story has the same spatial layout as the original creator intended.

5.3.2 Three-Day User Study

We evaluated SceneAR in a three-day field study with 18 remotely located participants. Before the study, we ran a pilot study with two remote participants as a dry run of the study and to get early feedback on the app's functionality for identifying and fixing technical issues.

5.3.2.1 Participants

Eighteen participants were recruited through word of mouth and mailing lists of various academic departments around the United States. Because we developed the SceneAR app using Google's ARCore SDK, we looked for participants who owned phones officially supported by ARCore. Participants were located in six different states of the United States, Brazil, India, and China. Participants included graduate and undergraduate students, engineers, software developers, and a chemist (12 male, 6 female), aged between 20 and 44.

App Usage Data Summary	
Published stories	194
Remixes	48
Self remixes	11
App usage time per user (average)	67 min
Sessions per user (average)	11
Session duration (average)	20 min
Unique 3D objects users	325
Total 3D objects	1204

Table 1 .Summary of SceneAR usage during the study.

Participants rated, on average, 4.1 on a 7-point Likert scale (1 = never before, 7 = a great deal) their familiarity with AR. Pokemon Go was the most common AR experience cited. Participants reported spending an average of 6.7 hours per week using personal devices like phones, tablets, or computers and 1.7 hours a week playing games on the phone or tablet.

Participants also reported posting visual content frequently on WeChat (2), Snapchat (7), and Instagram (9), including memes (6), GIFs (3), comic strips (1), and YouTube videos (2). Two participants reported rarely using social media.

5.3.2.2 Study Procedure

Pre-study

Because ARCore is only supported on recent devices, finding participants with official ARCore-approved devices was challenging. Therefore, potential participants were asked to install Measure (an AR app) and AZ (a screen-recording app) from the Google Play Store, record a session running Measure for 3 to 5 minutes, and report on device overheating, excessive battery drain, and any Measure app crashes. Our goal was to ensure ARCore could run on devices at least well enough for participants to successfully complete the SceneAR study tasks, even if they were not officially supported. Despite this test, some participants had severe issues with ARCore surface detection.

Onboarding

Each participant was onboarded in an online meeting using Zoom video conferencing software. This meeting lasted 40 to 50 minutes. At the beginning of the video call, we emailed the participants a consent form (study protocol approved by our office of research), a participant ID, a pre-study questionnaire, the app installer (APK), instructions on how to install the app, a document with information about the study tasks and how to use the app, and a drive link to upload their screen recordings. During the video call, we walked participants through all these items. Participants also screen recorded themselves creating a story and remixing a story during the Zoom meeting.

At the end of the Zoom session, participants were asked to use SceneAR as they pleased with a study task requirement to create a total of nine stories over the three days. We closed by scheduling a follow-up Zoom meeting three days later for filling out a post-study questionnaire, conducting a short interview, and showing participants how to remove the app from their devices.

5.3.2.3 Data Collection

Data were collected through screen recordings of app usage sessions, published stories, pre- and post-study questionnaires, and Zoom recordings of interviews. Because of the open and remote nature of the study, we asked participants to screen record all their app usage sessions and upload them to a secure folder at the end of the study.

After the three-day study, participants were interviewed using a semi-structured interview schedule, which lasted an average of 20 minutes. Before that, participants were asked to fill out a post-study questionnaire with two 7-point Likert scale (1 = strongly disagree, 7 = strongly agree) questions, along with questions about what they liked/disliked about SceneAR, the types of stories they enjoyed creating, barriers to using the app, and other open-ended feedback.

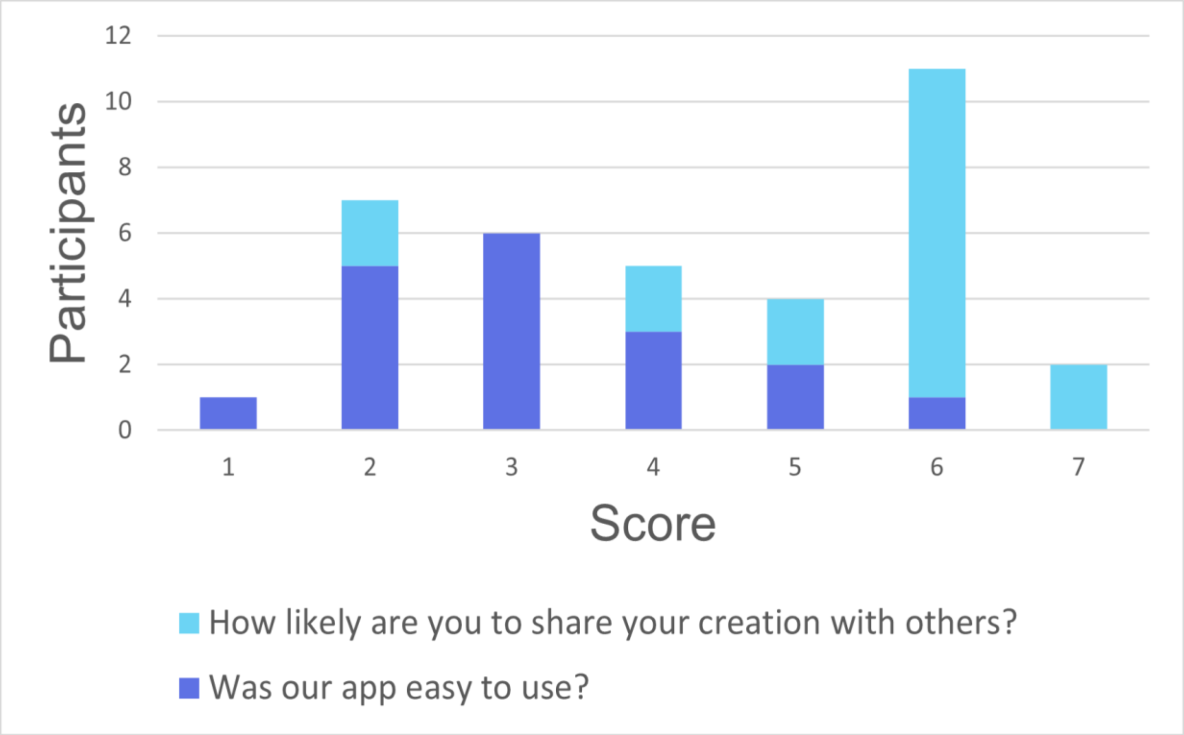


Figure 25. Participant (N = 18) responses to two questions in the post-study questionnaire asking 1) how likely are they to share a created micro story (1 = not at all, 7 = extremely likely), and 2) was the app easy to use (1 = very easy, 7 = very hard).

5.3.3 Data Analysis

We wanted to identify and quantify SceneAR usage, so the data were thematically coded by two researchers independently to determine characteristics and functionalities.

We employed an inductive thematic analysis approach to the data, as described by Braun and Clarke [201]. Participant interviews were transcribed from the Zoom recordings using an online service (sonix.ai)[10], and the text transcripts were exported for qualitative analysis. Screen recordings were matched with interview transcripts using the participant IDs. Two researchers independently reviewed these transcripts and recordings.

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[10] https://sonix.ai/

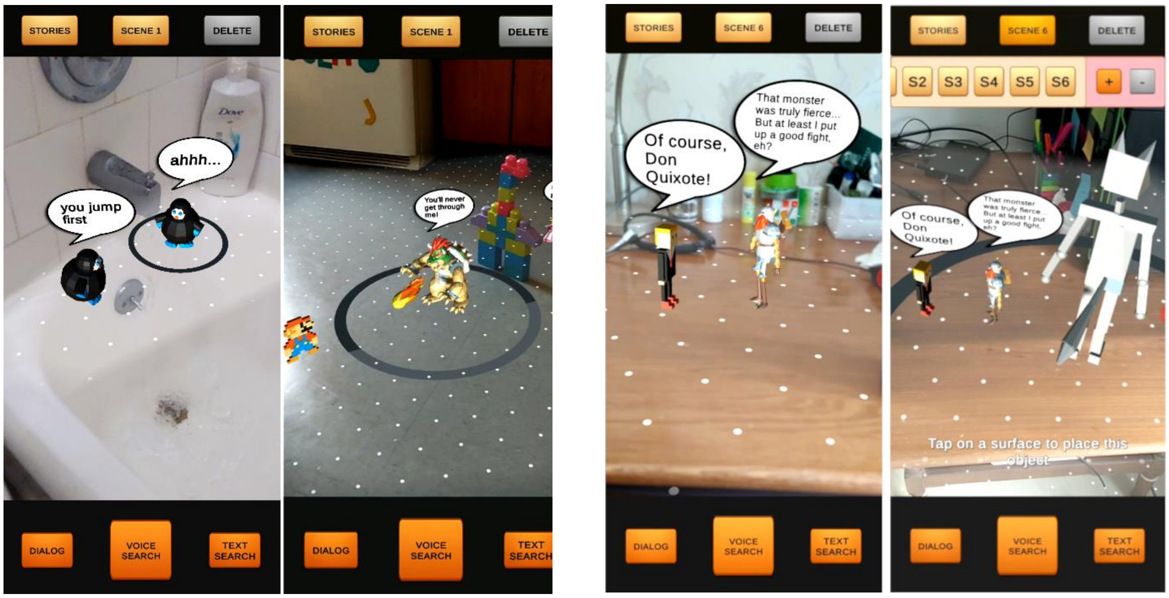
To make meaning from the screen recordings and the interviews, each researcher created their own codes. Following that, the researchers met over Zoom to discuss and refine their codes, which resulted in an agreement on 12 codes. These codes were further analyzed and referenced with the screen recordings and feedback in the questionnaires and then reviewed again by both researchers in another meeting. This approach identified three overarching themes, as discussed below.

5.3.4 Results

In this section, we present the responses to the post-study questionnaire and describe the three themes we derived from our analysis of the data: Diversity in Creativity; Spatial Creation and Viewing; and Sharing, Remixing, and Collaborating.

5.3.4.1 Questionnaire Responses

Likert responses are illustrated in Figure 25. Most of the participants found our app easy to use (1 = very easy, 7 = very hard), with a positive response median M of 3 and a median absolute deviation (MAD) of 1. Participants also agreed that they were likely to share their creations with others (1 = not at all, 7 = super excited to share) with $M = 6$, $MAD = 0$. To understand the reasons for these scores in the interview data, we found that two participants who rated our app as being not very easy to use had frequent ARCore-related surface detection issues on their devices. One user had an old phone model that did not provide a stable frame rate, and the other user was detecting surfaces under extremely poor lighting. On likelihood to share the creations with others, two participants rated it low, which matched their prior report



(a) (b)

Figure 26. a) Left: two penguins debating who jumps first while standing on the edge of a bath tub with the water running. Right: a re-creation of the Super Mario video game with Princess Peach hidden behind the physical toy castle and virtual Bowser defending it. b) This set of two screenshots shows a scene from the original story "*Don_Quixote*" by P5 on the left and the same scene remixed by P14 with the addition of a robot cat on the right.

on rarely using social media, with one saying, *"[Do] not post very often and pretty much never publicly share things like gifs or memes.*"

5.3.4.2 SceneAR Usage Summary

A summary of how participants used the app is presented in Table 1. Participants used SceneAR in bursts throughout the study, averaging about 20 minutes of app usage per participant per day. The minimum time spent in one session was about 10 minutes, whereas the maximum time was about 34 minutes. The minimum total app usage time over the three days was about 30 minutes, whereas the maximum was over 3 hours.

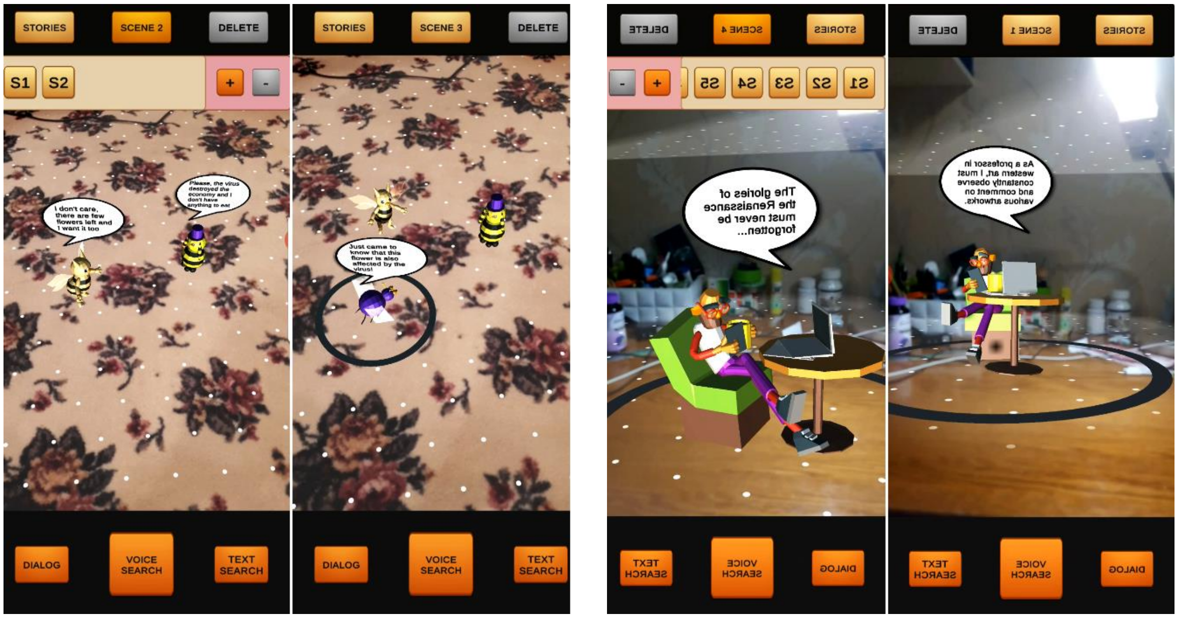
Across all 18 participants, a total of 194 stories were created, of which 25% (48) were remixes. Of the original stories, 26% had one scene, 32% had two, and 42% had three or more scenes. "*Mary had a little lamb*" by P17 had the most scenes of any story at 10, whereas "*Lonely_Cat*" by P5 was the second longest at 8 scenes. The longest remixed story had six scenes, titled "*remix_don_quixote*" (Figure 26), originally created by P5 with five scenes and remixed by P14 with a new scene. Of the remixed stories, 22% were remixes of stories created by the participant themselves, whereas the rest were remixes of other people's stories. The most used search keyword was "person" for a total of 142 times not including other related searches for "old man, girl, black woman, athlete, drummer, artist, Trump, etc." and fictional character searches like "Luke Skywalker, Iron Man, Mario, Captain Marvel, Darth Vader, Gandalf, etc." The top three story themes were COVID-19, music, and space.

5.3.4.3 Theme 1: Diversity in Creativity

This theme describes how participants were able to create the stories from various sources by using different narrative techniques. It is divided into four categories: Moments from Life, Media Inspiration, Improvisation on Visual Search, and Technique Transfer. We found that participants were eager to discuss the types of stories they created and why, requiring little to no prompting to describe their experience. Several participants expressed a desire to continue using the app after the study.

Moments from Life

A large number of stories created by participants depict moments from life, also commonly seen in digital storytelling media like memes, GIFs, and short-form videos. They cover topics such as home, relationships, recreation, politics, games, nature, etc. Among these daily life--themed stories, a variety of ongoing social events including the COVID-19 pandemic, space



(a) (b)

Figure 27. a) Scene one shows two virtual bees arguing about who gets the flowers on the physical rug because of the shortages created by the COVID-19 pandemic. A third bee joins them in Scene 2 to end their argument by saying the flowers are infected by the virus. b) Scene one shows an art history professor lecturing. The two scene screenshots show how the creator framed the professor, by scaling the model instead of moving the camera, inspired by their background in film making.

travel, and government policies (the international student ban, shelter-at-home orders, etc.) can be observed. COVID-19 stories specifically focused on the economic crisis, social distancing, mask wearing, Christmas without Santa, travel bans, and loneliness. For example, P8 created a digital-physical story in three scenes called "*bees in covid*" that showed virtual bees standing on a physical floral print rug and having an argument about who should get the flowers (Figure 27) in this time of crisis and shortage.

Media Inspiration

Participants narrated how much they enjoyed re-creating content from other media like movies and storybooks. The *tortoise and hare* story created by P4 was remixed by two others with new scenes and dialogues. P6 said, *"We can recreate remixes of different, like, stories that we've read before like Cinderella comes and picks up her shoe. Having a twist, maybe something is not similar, at the same time it's a visual depiction of that [something familiar]"*. P6 was interested in creating old stories that teach philosophy and morality. P7 created a space battle based on the movie franchise *Star Wars*, showing virtual ships and two 3D-printed ships, namely the Millennium Falcon and a TIE Fighter. The *Don Quixote* story was created and remixed in a playful way by several participants (Figure 26).

Improvisation on Visual Search

Participants improvised based on the app's responses to their search results supported by access to thousands of 3D models, though sometimes even that large set did not seem enough. We noticed that, during an object search, the selected 3D object does not always match perfectly with the intended keyword input. Some cases were due to the absence of a 3D model that matches the participant's expectations to use as a story component, which is a limitation of keyword-based search methods. However, in some cases, the participants were inspired by the visual results of a search and decided to dedicate the story plot to the found 3D object. This can be particularly observed in the story creation process by P13 where the story was originally intended to be a basketball game between Pikachu and Godzilla. P13 initially fetched a 3D model of a regular basketball but later found a spherical-shaped ball-like Pikachu while trying to fetch a regular Pikachu 3D model. This made P13 change the story plot into an ending where Pikachu becomes the ball in the basketball game, thus deleting the original basketball. Similar behaviors can also be observed in P16's creation process where one of the main characters of the story switched from a giraffe to a fox during the visual search of 3D objects.

Technique Transfer

Participants used their prior experience with other forms of media to help guide their 3D creative experience. A story by P5 composed of seven scenes titled *On_Art_History* is a monologue by a professor of Western Art speaking to his audience (presumably lecturing in class) (Figure 27). We noticed each scene was explored in a manner similar to framing shots in a film, something P5 expressed during the interview. About framing scenes, P5 said, *"Even though I did not use any real world objects, I was still able to enjoy the functionality of using different angles and sometimes making it big, sometimes make it small, sometimes make it distance, sometimes make it close."* P4 said, *"I'm into short films. This app, there are more 3D models and objects. I felt like it\'s more useful for future filmmakers and all to set their scene in this AR thing so they can show it to their crew and team member to like better understand director's vision."* P1 enjoyed placing objects in scenes and said, *"You are actually constantly a theater designer or stage designer. That's already like a whole another set of entertainment for me."* P4, P12, and P7 used onomatopoeic words commonly seen in comics (e.g., 'Raawr', 'VROOM', 'Zzzz', 'SCREECH', 'pew pew') and emoticons seen in text messaging in their dialog balloons to express emotions.

5.3.4.4 Theme 2: Spatial Creation and Viewing

This theme focuses on creating and consuming stories in a 3D spatial environment. We divided it into four categories: In Situ Authoring for Creativity, Spatially Stimulated Imagination, Story Setting, and Physical and Virtual Object Interplay. We found that our users specifically enjoyed the simplicity and speed of the scene creation process and did not remark upon or ask for inclusion of other features (sound, animation control, events, etc.) as necessary elements for telling their Micro AR stories.

In Situ 3D Authoring for Creativity

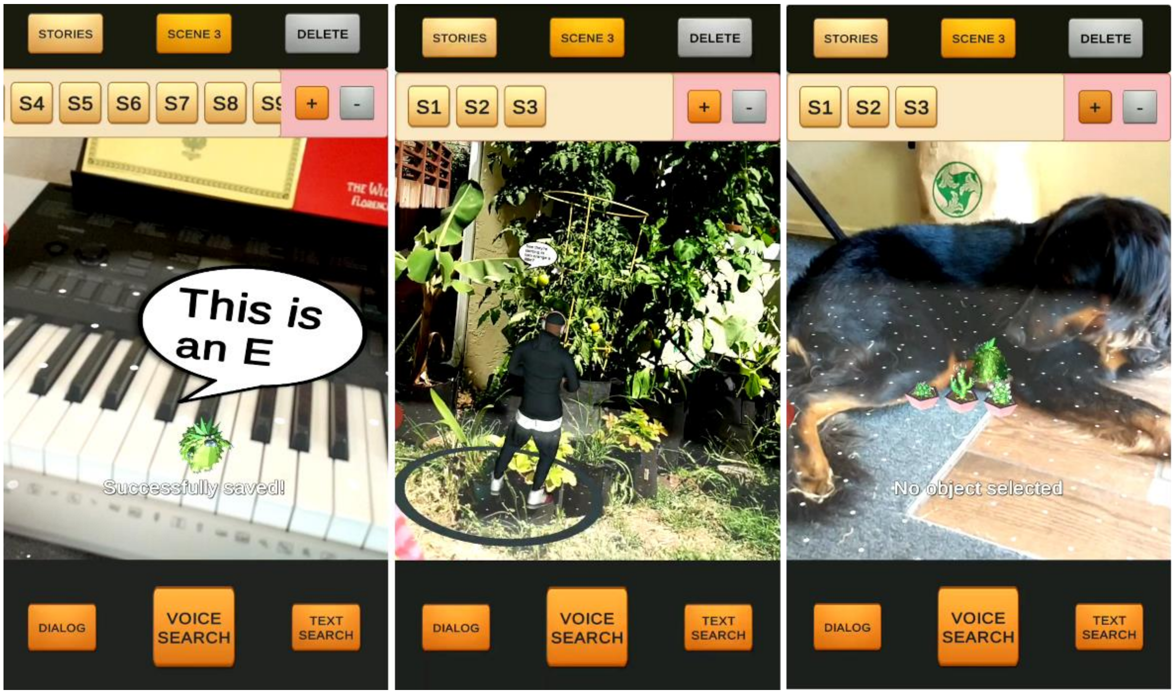
Participants expressed surprise and excitement about being able to create 3D content using their mobile devices. They reported that SceneAR enabled free-form creativity in AR, with 3D adding another dimension and enabling new possibilities that they had not yet seen in any other app. P5 said, *"It is just so cool, like you create some 3D scenes with dialog with different scenes, on a mobile device, in 20 minutes."* Some found 3D to be the next obvious step saying (P5), *"You create from drawings to moving frames, movies, then there are just more things to do. Right? I think there will be more storytelling ways, possibilities in this new platform."* Participants found the ability to express themselves in 3D liberating. P6 said, *"Having it in 3D just expands the scope. In 2D its just an image and it is quite constrained but in 3D like we can have like different scenes so it just expands the scope."* P12 remarked upon how stories in 3D *"become part of your world"* while P15 said the 3D aspect was *"definitely part of the appeal. There isn't really anything that is creating in the app in 3D and viewing in the app in 3D."* On 3D authoring enabling greater creativity, P4 said, *"We are going from 2D world to a 3D world and creating stuff. In 3D world a lot of other stuff can be include which we can't put on paper. It will help people be more creative and like convey the message that they want a little more clearly to others."* P17 said 2D has barriers but with SceneAR everything became much more limitless, though P3 worried that there may come a time when there are *"too many layers on top of what you're seeing and you are losing sight of what's really there."*

Spatially Stimulated Imagination

The ability to create virtual content with changing perspectives and realistic life-size scales seemed to have presented the participants with a new mental model for thinking about stories. In AR, stories and storytellers inhabit the same space, which is a blend of physical and virtual elements. Some found this new relationship helped them think of new ways to tell their story. P7 said, *"I found myself thinking of special stories content that I could create that I wouldn't otherwise be able to create using other platforms."* P8 expressed a similar idea about the scale of objects: *"This is like an environment where you can make anything kind of happen, like you can make robots talk or like flies be bigger than dinosaurs."* Participants found the ability to change perspectives a new way of experiencing a story. P3 said, *"[O]nce I realize I can move and see it from different angles and its like that, that helped coz you can be inside it from different angles where you sorta like can't with other ways like drawing or whatever, you can't be like inside it!"*

Story Setting

We noticed participants created their stories in different settings around their homes---from bathrooms, kitchens, and hallways to bedrooms and front yards. P15 created a story called *"penguins go swimming"* where virtual penguins debate who will jump first while standing on the edge of a physical bath tub (Figure 26). P15 created another story on the kitchen counter introducing a virtual cookie to a physical one. Understandably, these stories require the viewer to have similar physical conditions to experience the story as designed. When asked about blending the real and the virtual, P15 said, *"[It] is a really fun and exciting new mechanism for people to share their creativity."* P14 echoed that sentiment, saying, *"I think it's the*



Successfully saved!

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Figure 28. Three micro stories created by P18 that connect virtual objects with the real world. Left: A 10-scene narrative that teaches how to play "Mary had a little lamb" on the piano. Middle: A story set outdoors where the character explains how to recognize different tomato plants. Right: The dog being mildly annoyed by virtual bugs.

opportunity to mix real world with fiction AR." P18 was the only participant who made stories outdoors, one story showing their vegetable garden, another one teaching the viewer how to play a song on the piano, and yet another one attaching virtual bugs to their dog (Figure 28). When asked, P18 remarked, *"Every new tool is a new way to think about things and do things in different ways."*

Physical and Virtual Object Interplay

In addition to setting a story in a physical place (e.g., kitchen counter), we noted that participants created stories with physical objects. P7 created a fictional story based on the popular video game franchise Super Mario using the game characters and a physical toy castle

(Figure 26) as the main elements. P6 expressed a desire for more interaction with physical objects saying, *“If I could use dialogues on physical objects, even though there was no object detection, I could just put a dialog.”* P7 said their favorite part was *“making the digital and physical worlds act with each other.”* These participants demonstrated a different type of relationship between the physical and the virtual, one where the setting has no relationship to the story but the story itself integrates physical and virtual elements, for example, a toy castle with the virtual Mario (Figure 26) P7 created two stories (*“Mario”* and *“Star Wars”*) that incorporated physical objects like toys and 3D-printed space ships, but not the physical location, into the stories.

5.3.4.5 Theme 3: Sharing, Remixing, and Collaborating

This theme relates to participants being able to share and remix stories made by others in AR, unlike anything they reported having seen or tried before. Our new *Micro AR* story packaging method enables easy sharing and remixing of the user-created AR scenes. The four categories are: Stories for Sharing, Remixing, Inspiration from Community, and Communication and Collaboration.

Stories for Sharing

A fundamental aspect of storytelling is the audience. All participants in our study enjoyed creating and sharing stories as reported on the post-study questionnaire. P7 likened people using SceneAR to those creating short-form video stories on TikTok[11], saying *“[P]eople that are good at making shorter funny content that would have a blast with adding these [3D] new*

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[11] https://www.tiktok.com/en

elements into the scene." The desire to include friends in stories both directly as avatars and indirectly as people to share stories with was expressed by several participants. Some participants added characters that resembled their friends, and some expressed a desire for the app release to include a feature that would allow them to import photos of their friends into the 3D scenes.

Remixing

The idea of collaborative remixing [202] is evident in participants creating stories specifically for others to remix. For example, P8 says, *"I made it [a story about wormholes] so that other people would have like good remix ideas for it."* All participants remarked upon the novelty of remixing AR scenes and how much they enjoyed it. P11 was the only participant who did not create any remixes, being one of two people (other being P3) who also mentioned not posting on social media. Nevertheless, P11 created the most stories (13) of anyone in the study. We would like to believe that they found their medium of creativity in SceneAR. P1 also did not create any remixes saying, *"I never felt like I have a motivation to trying to do it. Like storyline is so complete a lot of time that it's better to just start over sometimes."* Six participants explicitly mentioned enjoying seeing remixes of their own stories or creating their own remixes, which we call self-remixes. P2's remixed story presented a continuation of one idea from the first story to the fourth one with each new story adding new scenes, characters, and objects (Figure 26). They said, *"[Remixing] is really cool, like seeing other people part of your story."* Of those who enjoyed remixing, P8 said, *"Remixing stories was like a lot of fun, yeah, that was definitely very interesting."*

Inspiration from Community

During the interview, participants highlighted that the ability to remix made creating stories much easier. One participant contrasted the mindless ease of taking and sharing a photo on Instagram with putting a lot more care and purpose into the design of their scenes. P5 said, *"Most of the time I would start from seeing somebody else's work. It would give me inspiration. If it's really good I would just expand on that. I see it as a source of motivation, giving you ideas."* P10 said, *"We can follow the idea from other people and then build on top from it."* Three participants said coming up with creative or clever ideas was the hardest part of using the app. P4 said, *"For me, was the creativity to create the stories."* P14 also said the creativity was the hardest part for them and being able to remix was helpful: *"You can pick idea of another person and improve this, so I think is very nice."* P1 thought the app allowed open-ended creativity like Lego blocks but, unlike Legos, where you are constrained by the pieces you have, SceneAR gives you *"unlimited 3D objects, unlimited resources to create your own work."* P17 wanted the app to give them suggestions for objects *"based on the physical space recognition"* to make the experience more intuitive, such as creating stories related to living rooms if they are in the living room.

Communication and Collaboration

We noted that remixing afforded a novel form of back-and-forth communication between participants where one person expressed their thoughts and emotions through a story and another person remixed it only to be remixed again by the first person. P2 remarked, *"We don't want to build everything from scratch. I need some existing background that I can put my people and you know start like conversation."* P12 found remixing a good way to *"share* *imagination and creativeness with each other."* P12 said that seeing other people modify your stories gives you an understanding of how they have interpreted your work. During the interviews, participants expressed a desire to have a social network and the ability to create these back-and-forth narrative-based dialogues with friends. P6 said, *"if I could have friends on this app and I can share the story and they could render it in their surroundings, like they could load it in their surroundings, then I can like ask them to edit, so it would be like a collaborative creation."*

5.3.5 Discussion: Strategies for Supporting AR Storytelling

Here we articulate six design strategies that we derived from our data analysis and participant feedback. These strategies can serve as a guide for the development and design of future AR short-form storytelling systems that allow users to create, share, and remix 3D scene-based narratives on their mobile devices.

5.3.5.1 Consider Spatial Dependencies

One of the challenges with sharing AR stories is that the creator's physical environment is likely to differ from the consumer's. For example, an AR story can have contextual dependencies, such as the size of the detected plane, which might impact the position and rotation of AR objects. This could happen if, for example, the creator uses a large dining table to create the story and the viewer tries to render it on a small coffee table. Similarly, a creator might compose a story on multiple detected planes. For example, a creator might create one scene on the floor and a subsequent one on a table. If the person viewing the story does not have an environment with two planes at different relative heights, some virtual objects might appear to be floating. These differences can create a disconnect between the virtual objects and physical surfaces, which can break the illusion of realism for the viewer. Until smartphone devices with LIDAR sensing become commonplace and users are willing and able to share their entire physical environment, one way of mitigating the challenge of spatial dependencies is to guide the story consumer to arrange their physical environment to match what the creator had in mind more closely, something people usually do for watching football games together. SceneAR does this through the story description.

5.3.5.2 Include Spatial Navigation

The story consumer has complete control over how and where they view the AR scenes. However, this can negatively impact the viewing experience owing to accidental camera movements. For example, if the person places a scene on the floor and happens to turn around, that scene will fall out of the camera's viewport. In such scenarios, locating the scene again with the camera's viewfinder, without virtual visual guidance, may be difficult. One way to resolve this is to provide directional arrows that point the viewer toward the center of the scene, especially if they are noticeably off-track from finding the scene with their camera. More complex 3D navigation information is needed to guide the viewer in multi-plane AR stories.

5.3.5.3 Recognize Camera Clutter

The ease with which creators can add virtual objects to a scene can lead them to crowd the camera's viewport and make it difficult to interact with the objects in the scene (e.g., selecting, scaling, moving). Some of our participants reported this problem. Designers can mitigate this problem by exploring different narrative structures, such as timed objects or plane-to-plane movement, to prevent AR objects from overcrowding a single viewport.

5.3.5.4 Enable Support for Contextual Constraints

The differences between the creator's and viewer's environment introduce some semantic challenges in addition to the spatial ones described above. For example, a viewer would miss some of the story's context if they saw the story about the two penguins (Figure 26) in a place without a bathtub. It would not present exactly as the creator intended. Again, once LIDAR sensors in mobile devices become commonplace, sharing the story context in 3D will become simpler but might introduce its own set of challenges like privacy. Meanwhile, a simple way to alleviate this challenge is by listing physical dependencies of the stories and leaving the consumer in charge of their AR experience of that story. Effective storytelling in AR truly augments a user's reality; hence, describing the type of reality the creator intended to augment is necessary until we are able to easily create and share the 3D context with each AR narrative.

5.3.5.5 Assess Surface Detection Limitations

Unlike traditional touchscreen apps, creating and viewing stories in AR requires physical movement to scan the physical space, detect planes, and move around for an immersive experience. Several factors can impact surface detection, including the user's device, lighting, clutter, and textures (or lack thereof). Repeated surface detection failures can make the AR experience feel onerous. One way to mitigate this issue, for the creator and the viewer, is to often save or cache the story content to prevent the story from disappearing when the detected surface is lost. While newer Android devices can support Depth APIs [203, 196] and newer

Apple devices have LIDAR sensors, both of which can improve the user's AR experience, most people do not own these devices yet, especially if we want to consider bringing AR to the billions of mobile devices in use worldwide.

5.3.5.6 Offer Help with Writer's Block

People can feel intimidated when creating a story from scratch, as some of our participants reported. Although this is not unique to AR, the spatial nature and even the novelty of AR might exacerbate this problem. One way to mitigate this is to scaffold new stories through previous stories, such as by allowing people to remix other people's stories as supported in SceneAR. Other options include offering in-app suggestions or templates. For example, the app can detect the user's location (e.g., a public park) and offer a story template based on it, or, as one participant suggested, the app can offer suggestions for virtual objects based on physical object recognition in their immediate environment. Although suggestions can be helpful, systems that scaffold (e.g., for novices) and support open-ended explorations for experts would allow us to build on decades of user-centered research in the design of web and mobile interfaces. Interestingly, participants commented that SceneAR could be the next AR meme generation app because of its rich data set of models and the freedom to create, share, and modify combinations of visuals and text.

5.3.6 Limitations

Our research provides insights for using AR as a storytelling platform for creating scene-based micro narratives. However, our work has some limitations. We focused on understanding how people would use an AR storytelling app and the opportunities and challenges that would arise. We chose to evaluate SceneAR as a minimal viable prototype, directing the user's efforts toward the creating, publishing, viewing, and remixing of micro stories rather than optimizing elements of the UI or adding more complex features. With informal testing, and later with the pilot study, we realized that users are not familiar with AR; namely, they do not understand how to scan, what types of surfaces make good candidates for plane detection (e.g., not blank walls or floors or white tables), nor do they realize the impact of low lighting levels on surface detection and tracking, to name a few. Therefore, while our original application had complex elements like hand gesture recognition and finger-based drawing in space, we chose to keep things simpler for the evaluation. We plan to investigate the multi-modal input modalities (gesture, speech, and touch) in a more controlled lab environment once we are allowed to do so in the fall. Although conducting the study with remotely located participants increased the complexity of the study design, we believe it also helped us learn things about AR use we may not have learned in an in-lab study, as mentioned above.

Additionally, the demographics of our sample may have biased our results. While the average age of our participants might align with those who are more likely to use creative or social media apps, our sample does not include older adults or children (i.e., those 18 years and below). A future study of two larger groups of users---with and without storytelling or creative backgrounds---may help us better understand narrative strategies and functionalities of our system beyond the end user social scenario considered in this work.

5.3.7 Summary

We presented SceneAR, a mobile AR app that enables users to create, publish, view, and remix scene-based micro narratives in AR. We detailed the design and implementation of

SceneAR and presented findings from a three-day field study with 18 participants. Remixing enabled a new form of visual communication between participants, both by modifying a story and watching others modify and remix their stories. Conducting the study outside the lab environment revealed design tensions in AR apps primarily due to ARCore issues related to reliable surface detection and environmental conditions like lighting, surface textures, and clutter. Participants expressed a desire for a social network where they can create longer story-based communication threads, in both private and public conversations, or use the app to create AR memes. Based on the study, we outlined design strategies for AR scene-based narrative systems, highlighting characteristics unique to smartphone-based AR.

5.4 EntangleVR (2021)

Virtual reality (VR) has seen significant growth in recent years and demand for new types of experiences is rising. Narrative experiences can harness the power of VR to allow users to

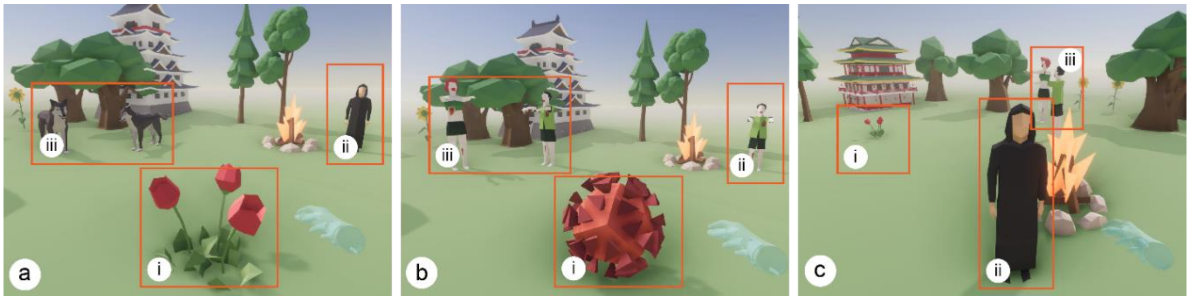


Figure 29. An example interactive VR scene with different possible outcomes that depend on the user's interactions with the scene elements. The scene shown is composed using EntangleVR's visual interface. Left: (a) the initial scene state that a user sees before interacting with any elements. Three interaction options and resulting story pathways are available where a flower (i) turns into a virus when touched by the user; a man in black (ii) is saved from becoming a zombie if the user chooses to visit him before exposing the virus hidden in the flower; and a wolf pack (iii) is affected by the user's interactions with either the flower or the man in black, turning them into zombies. Middle: (b) the user chooses to touch the flower which unveils a hidden virus (i), causing the man in black (ii) and the wolf pack (iii) to turn into zombies immediately. Right: (c) the user chooses to interact with the man in black first which save this character from becoming a zombie (ii) but still turns the wolf pack into zombies (iii). In (c), the user interacts with the flower (i) and discovers the virus behind the zombies.

experience the impossible such as step into Van Gogh's vividly colored paintings [204], take an intimate look into an immigrant family's struggles during the war [205], or explore the insides of the human body [206]. Many VR artworks [35, 207] and short-film experiences [208, 209, 210] use this new medium to present interactive narratives. These experiences are often driven by the user allowing them to explore the immersive environments via simple interactions such as touching and picking up virtual objects, or making eye contact with virtual characters. However, in most of these experiences, the user's interactions do not have any impact on the virtual landscape or the story-line, as the main narrative components tend to be scripted with linear progression. Even in highly interactive VR games, the narratives are often pre-scripted with no lasting cause-effect relationships leading to similar experiences for all users with a 'one size fits all' approach. We believe there is potential for first person VR experiences, much like real life, to be individualized with dynamic and unpredictable paths and endings based on a user's interactions. The ability to construct unique user-centered experiences in VR with simple mechanisms to support a multiplicity of outcomes can help reinvent the old design space of *Choose Your Own Adventure* narratives, enabling the creation of new types of immersive experiences by content creators such as artists and storytellers.

Existing methods for creating interactive VR experiences with outcomes that are based on a user's input require considerable programming experience, time and effort. This is usually accomplished with professional game development engines such as Unity [211] and Unreal [212]. Newer VR authoring tools focus on composing virtual scenes with customized 3D models and animated effects [213, 183, 214, 182, 215, 216] but they provide very limited support to add logical behaviors to these virtual objects [217]. Creators without sufficient programming experience may find limited options that allow them to build complex VR experiences that have multiple different outcomes driven by cause-effect relationships between the user's interactions in VR and the virtual objects. Unity and Unreal do provide visual interfaces to reduce programming complexity. However, despite the visual programming option, these tools still require the creators to have substantial programming knowledge and experience to create meaningful user interactions that can have an impact on the VR narrative experience and its outcomes.

To simplify creating VR experiences where a user's interactions lead to different outcomes (e.g., changing a series of virtual object properties and states based on user input), we developed EntangleVR, an interactive virtual scene composer. Creators can use our scene composer to build connections between a user's interactions and the narrative elements in VR through a simple visual interface. Specifically, we added a workflow to build interaction-driven experiences using a virtual scene composer with objects that are entangled in relationships with one other. Figure 29 shows an example VR scene created with EntangleVR that supports different outcomes based on a user's interaction choices. The visual interface aims to enable creators to build complex experiences with sequences of cause-effect behaviors without the need for any programming, in contrast with existing virtual interfaces for VR design.

We borrow the idea of *entanglement* from quantum computing to simplify the design of VR experiences with different outcomes. In our visual interface, entanglement is used to describe complex inter-object relationships where object states are mutually dependent on each other. Different from a classical cause-effect relationship where one object's state is usually considered a trigger that has an effect on another object's state, the states of two entangled objects are always correlated upon an event triggered by user interaction without a clearly defined causal order. A single interaction from the user is taken as a measurement in quantum computing and can easily affect an entire entangled group and collapse the object states in many different ways. For more complex multi-entity scenarios, the cause-effect link between many objects can quickly become difficult to predict and track. A chained series of events can contribute to different outputs depending on the order in which they are triggered by the user. This type of complex scenario is usually accomplished with multiple if-else statements in programming but in our system, entanglement can be used to construct non-separable behaviors of entangled objects, allowing the creators to easily follow and control the sequences of cause-effect behaviors through the visual interface.

We wanted to understand how well our EntangleVR interface with embedded entanglement would work for creators to help them build interactive VR scenes quickly and easily. We asked 16 people to use EntangleVR in a 90-minute study. Based on interviews, analyses of screen recordings, and questionnaire feedback, we evaluated the usability of the system and its capacity to support easy creation of entangled behaviors of virtual objects summarized into four themes: expressive visual interface, creation with entanglement concept, diversity in creative activities, and learning support for basic quantum concepts. The study results demonstrate that the concept of entanglement can possibly be applied to VR scene creation, interactive storytelling, puzzle game design, and creative arts. The main contributions of this work are:

- A visual programming interface and workflow to support fast creation of multi-object behavioral relationships in the design of a VR experience.
- A new method to allow creation of interactive relationships between object properties and user interactions via entanglement.

- An evaluation of the EntangleVR system by participants with four themes derived from data analysis on learning and creating with our system.
- Four authoring strategies for creators and storytellers exploring VR for interactive narratives

5.4.1 System Design

The EntangleVR visual programming environment is built as a plugin for the Unity game engine with a node-based graph interface and a custom-built quantum simulator written with Math.NET library [218] to enable basic quantum operations and support quantum-like indeterminacy. The system allows the user to create different nodes that allow composing interactive virtual environments. Immediate visual feedback is provided through the composed scene as and when the node parameters are modified.

5.4.1.1 User Interface

EntangleVR aims to provide an easy and straightforward interface for VR content creators. The interface has a single window containing all the key components where users can select and create nodes, compose graphs, and interact with the visual output, all at the same time.

Figure 31 shows the EntangleVR interface, which has four main panels. The lower left panel is the Toolbox with buttons to create nodes. The middle panel is the graph canvas where created nodes appear and can be connected to formulate a graph. The upper left panel is an interactive preview which renders the visual results of the graph in real-time as the nodes are being edited. The rightmost panel contains a tutorial and step-by-step walkthrough of the

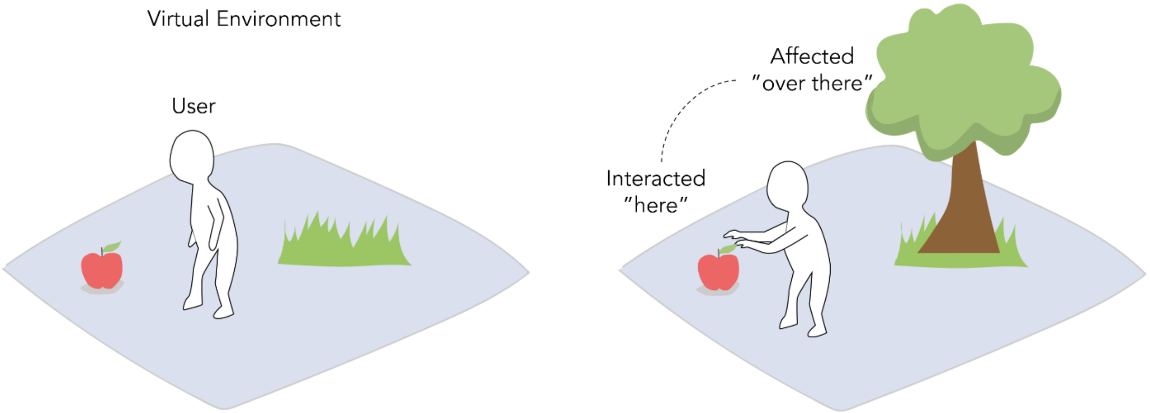


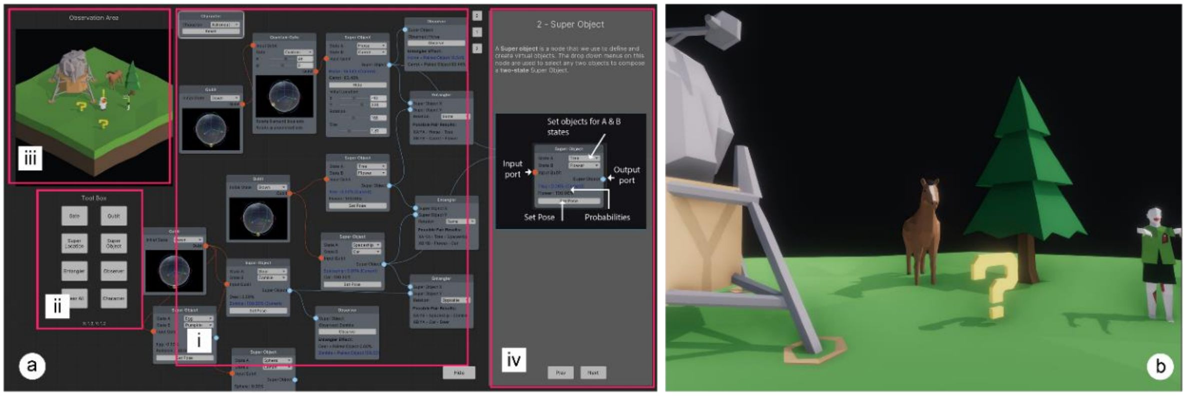
Figure 30. A brief overview of the design concept for EntangleVR. A user in a virtual environment can perform an interaction to a virtual object, and this action affect another object somewhere else in the space as there is an entangled relationship between the two objects.

interface as well as the integrated quantum concepts. This can be turned on/off by the user at will.

5.4.1.2 Quantum-inspired Node Design

EntangleVR enables users to create 3D virtual environments by connecting nodes together to formulate a relational graph of virtual objects. The nodes in EntangleVR can represent object instances, logical statements, and control events. All the nodes have input ports on the left and output ports on the right. The ports are type-constrained and their colors inform the user if they can be linked together. There are seven types of nodes in EntangleVR: Super Object, Qubit, Gate, Observer, Entangler, Super Location, and Avatar. They are all inspired by either quantum computing or quantum phenomena and contribute to the probabilistic quantum-like behaviors of the virtual objects. Figure 32 shows a selected set of nodes in EntangleVR system.

Qubit - A qubit node provides the basic unit of computation same as the one in quantum computing. To aid comprehension, we include an interactive Bloch Sphere representation [219]



A **Super object** is a node that we use to define and create virtual objects. The drop down menus on this node are used to select any two objects to compose a **two-state** Super Object.

Figure 31. EntangleVR system overview. Left: The visual programming interface where (i) is the main canvas to draw node-based graphs (ii) is the Toolbox with buttons to create nodes, (iii) is the real-time interactive preview which renders the visual results of the graph, and (iv) is the tutorial panel. Right: (b) shows the first person view of a VR scene created with EntangleVR.

in the node block to immediately depict the states of a qubit with a clear geometric reference to its basis vectors such as “Zero”, $|1\rangle$ as “One”, $|+\rangle$ as “Super Plus”, $|-\rangle$ as “Super Minus” [191].

Super Object - This node is a higher-level mapping of a qubit’s computational basis ($|0\rangle$ and $|1\rangle$) into virtual objects. A two-state object is designed to simulate the uncertain superposition nature of a qubit, and the created super object by default has a 50% chance to be measured or observed at *state A* (e.g., a banana) and 50% chance to be in *state B* (e.g., an apple). A qubit can be fed into a super object as input to replace and change the probabilities of the two states using the qubit’s probability amplitudes. Once this node is created, a super object icon appears as a question mark in the preview panel since it can be in either of the two states. The user can move its position, orientation and scale by changing its parameters.

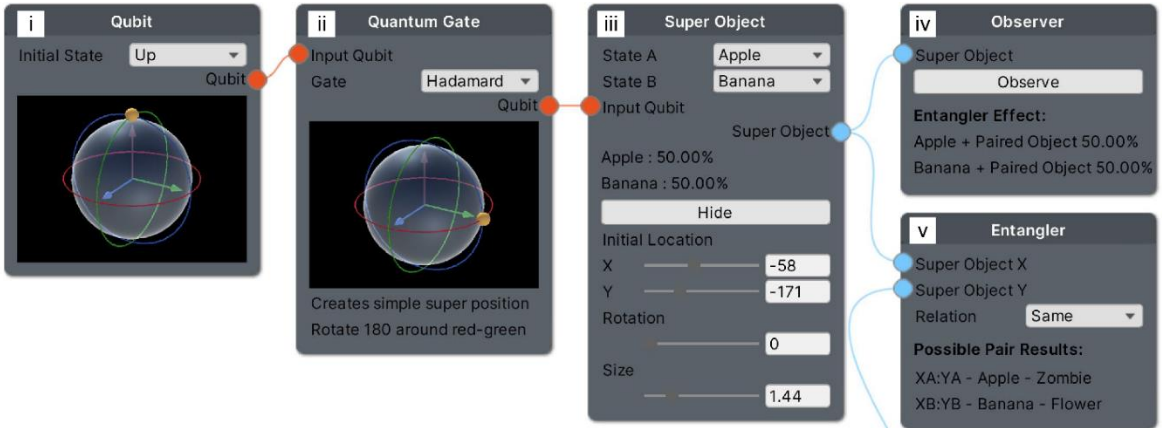
Observer - An observer node provides an interaction method to measure and collapse the linked super object i.e., set it's state to A or B, using a default computational basis $|0\rangle$ and $|1\rangle$. The user can choose to observe the super object and turn it into a classical state based on the amplitudes of states A and B. Observation can be triggered by three interaction methods:

1. VR mode - touching the super object with a virtual hand and clicking the trigger button on the VR controller,
2. 2D mode – in the 2D observation window, controlling the virtual character's avatar to approach the super object and double-clicking the super object, and
3. Preview mode - clicking the “Observe” button on the node block.

Upon observation, the super object, instead of showing as a question mark, will change its rendered icon to one of the two states (e.g., apple or banana).

Gate - A gate node provides a selected set of common single-qubit quantum gates such as Hadamard gate, Pauli X gate, and Phase T gate. These logic gates allows the user to manipulate the qubit state and interactively change the amplitudes of the target qubit via the visual interface.

Entangler - The entangler is built to simulate the unique quantum phenomenon of entanglement that is not available (but can be simulated) in the classical computing domain. An entangler node links two super objects (in total four possible states) and creates a non-separable and always-correlated relationship between them when one of the super objects is observed i.e., it's state is set. User can select between the two expressions (“Same” mode and “Opposite” mode) on an entangler. That is to say, user can give this non-separable state different amplitudes based on their interaction choice with one of the super objects. In VR mode, for example, the user can approach and interact with any super object. As soon as the user chooses a super object as their target of observation, an “observer effect” gets triggered on both the entangled super objects. The probability amplitudes of this user-selected super object's qubit (the main qubit) will be used as the amplitudes for state $|00\rangle$ and state $|11\rangle$ (or during “Opposite” mode for state $|01\rangle$ and $|10\rangle$). Eventually the two qubits “collapse”



Initial State: Up
Qubit

Input Qubit
Gate: Hadamard
Qubit
Creates simple super position
Rotate 180 around red-green

State A: Apple
State B: Banana
Input Qubit
Super Object
Apple : 50.00%
Banana : 50.00%
Initial Location
X: -58
Y: -171
Rotation: 0
Size: 1.44

Super Object
Entangler Effect:
Apple + Paired Object 50.00%
Banana + Paired Object 50.00%

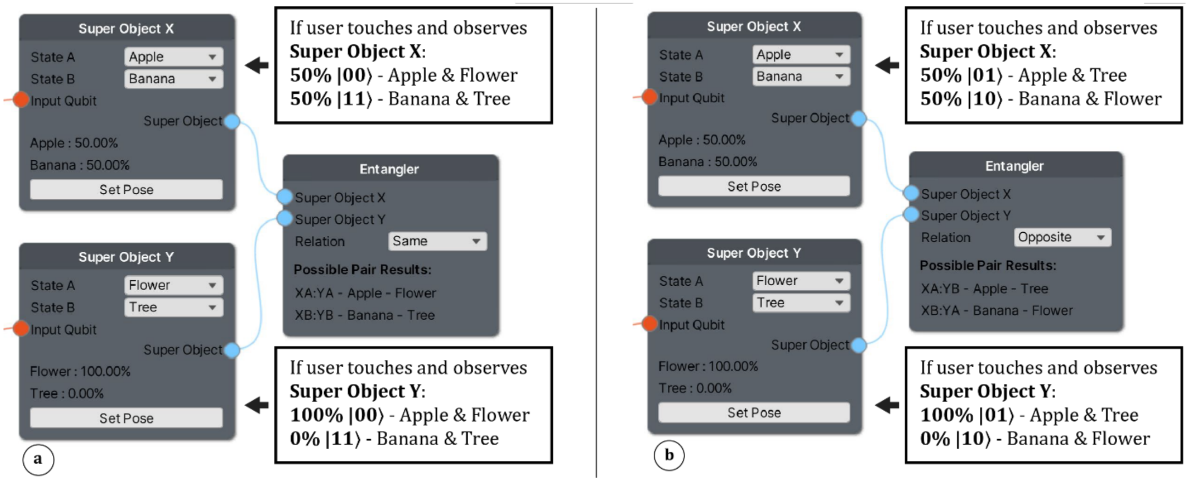
Super Object X
Super Object Y
Relation: Same
Possible Pair Results:
XA:YA - Apple - Zombie
XB:YB - Banana - Flower

Figure 32. EntangleVR's quantum-inspired node design. Left: (i) is a Qubit node in an initial state of $|0\rangle$ (Up). Left center: (ii) is a Gate node set as a Hadamard gate. Right center: (iii) is a Super Object node with a 50% probability of turning into either state A (apple) or state B (banana). Right: (iv) is an Observer node reflecting the expected measurement outcome of input super object. (v) is an Entangler node that entangles two super object together by a user-set relation.

simultaneously into correlated classical states depending on the probability amplitudes of the main qubit. Figure 33 shows an example of how user interaction can play with the entanglement effect. Please also see the Appendix for example usage of entangler for scene composition.

5.4.1.3 Probabilistic Control over Virtual Objects

In contrast to existing VR scene authoring systems, EntangleVR uses probability distributions to control virtual objects. Users create super objects to compose the virtual environment and these super objects, including their properties, behave probabilistically based on the state of the driving qubit. By providing a handle over these driving qubits via gates and the entangler, a user can create a state of *controllable randomness* defined by the probability amplitudes that they can set on the super objects. This can help simulate outcomes more akin of what might happen in real world scenarios where outcomes with 100% certainty are often unknown. At the same time, switching to a measurement in different basis other than the



Super Object X
State A: Apple
State B: Banana
Apple : 50.00%
Banana : 50.00%

Super Object Y
State A: Flower
State B: Tree
Flower : 100.00%
Tree : 0.00%

Entangler
Super Object X
Super Object Y
Relation: Same
Possible Pair Results:
XA:YA - Apple - Flower
XB:YB - Banana - Tree

If user touches and observes **Super Object X**:
50% $|00\rangle$ - Apple & Flower
50% $|11\rangle$ - Banana & Tree

If user touches and observes **Super Object Y**:
100% $|00\rangle$ - Apple & Flower
0% $|11\rangle$ - Banana & Tree

Entangler
Super Object X
Super Object Y
Relation: Opposite
Possible Pair Results:
XA:YB - Apple - Tree
XB:YA - Banana - Flower

If user touches and observes **Super Object X**:
50% $|01\rangle$ - Apple & Tree
50% $|10\rangle$ - Banana & Flower

If user touches and observes **Super Object Y**:
100% $|01\rangle$ - Apple & Tree
0% $|10\rangle$ - Banana & Flower

Figure 33. An example of how the entanglement effect between two super objects of different probability amplitudes can be played by the user interaction. Left: (a) shows the "Same" effect leading to a $|00\rangle$ or $|10\rangle$ state. Right: (b) shows the "Opposite" effect leading to a $|01\rangle$ or $|10\rangle$ state.

default computational basis can dynamically shift all the probability distributions in the entire virtual environment, allowing more creative play and control.

5.4.1.4 Interaction with Chained Object States

Multi-entity entanglement can be achieved by connections between three or more super objects. Depending on which super object a user first chooses to interact with, the results of the *collapse* from a multi-entity entanglement can vary considerably. The order of collapse is determined by the starting object following a breadth first traversal through all its connected nodes. Those objects that have already *collapsed* into classical states will not *collapse* again. This creates unique patterns of object state sequences based upon the user's interactions while providing the creator control over the outcome in different scenarios. The user can therefore create a mini "butterfly effect" situation with a high number of pattern combinations and possibilities by introducing many participating entangled elements. Figure 34 shows an example of entanglement between three super objects and different outcomes from each interaction choice.

5.4.2 Evaluation

We conducted our user study with 16 remotely located participants over Zoom video conferencing software to evaluate the usability of the EntangleVR system and its capacity to support creation of interactive VR experiences by the concept of entanglement. We specifically designed our evaluation to learn whether participants were able to use our visual programming interface to create interactive virtual scene of different outcome based on user interaction and to determine if the concept of entanglement in producing complex object relationships was understandable and usable.

As the goal of our evaluation is to gain insights into the interactive scene creation process using the visual programming interface, we did not require our participants to have a VR headset to experience the created virtual scenes. They were, however, asked to complete scene creation tasks with the output of their creation visible in the interactive preview window. Before the study, we ran a pilot study with two remote participants to get early feedback on EntangleVR's functionality and user interface for identifying and fixing technical and user experience issues.

5.4.2.1 Participants

Sixteen participants (10 male, 6 female), aged between 18 - 44, were recruited through mailing lists of various academic departments on our campus. Since EntangleVR is designed for running on Windows, we looked for participants who had a PC desktop or laptop.

Participants were from a wide range of backgrounds such as computer science (2), media arts (6), music (1), electrical engineering (6), and business (1), and they all had different levels of experience with programming in general as well as familiarity with quantum computing.

Participants rated, on average, 5.8 on a 7-point Likert scale (1 = not at all, 7 = A great deal) regarding their familiarity with scripting-based programming. Python was the most common programming language reported (13 participants). Participants also rated on average of 2.8 on a 7-point Likert scale (1 = not at all, 7 = A great deal) regarding their knowledge of quantum physics or quantum computing. On visual programming experience, participants rated on average of 3.0 on a 7-point Likert scale (1 = not at all, 7 = A great deal) with Max/MSP [220] as the most common visual programming languages reported (6 participants).

5.4.2.2 Study Procedure

Pre-study

Since EntangleVR is a plugin for Unity on Windows OS, potential participants were asked to install Unity game engine to make sure the VR authoring environment matched the development environment.

Onboarding

Each participant was onboarded in a Zoom video conference session. The total study session lasted 60 - 90 minutes, including the onboarding. At the start of the video call, we emailed the participants a consent form containing study protocol approved by our Office of Research, a unique participant ID, a pre-study questionnaire, and a link to download our Unity package containing the EntangleVR plugin. After providing informed consent, we

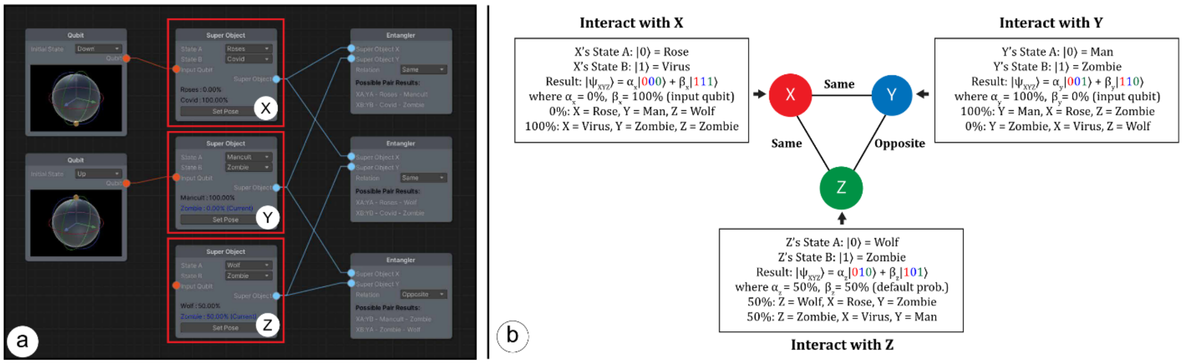


Figure 34. An example of how to build entangled relationships between three super objects in EntangleVR. Left: (a) shows three different super objects (X), (Y), (Z) that are defined with individual input qubits and object states, and are linked with entanglers. Right: (b) shows a detailed explanation of how the graph in (a) enables the user to achieve different outcomes based on interactions with X, Y and Z.

walked participants through all the items and guided them to install EntangleVR. After successful installation, participants were asked to complete two 15-minute long interactive tutorial sessions, each followed by a 10-minute scene creation task to evaluate the usability of the system, their understanding of the entanglement concepts, and the support for creativity and easy creation of interactive VR experiences.

Tutorials and Tasks

The study tutorials had two sessions: 1) learning how to create an interactive scene populated by super objects and super properties using qubits and gates (8 individual levels), 2) learning how to entangle multiple virtual super objects that can be observed interactively to have multiple outcomes by the preview avatar (4 individual levels). The first session had extra beginning levels that contained the basics of visual programming and user interface guidance that were necessary for the entire experiment. Participants also did short exercises at the end of each tutorial level to get them familiar with the control and editing interface.

Task 1: Create super objects	Task 2: Create an entangled scenario
Step 1: Create two super objects Step 2: Set your first super object with these properties: a) 50% chance of being a Horse, 50% of being a Deer. b) Appears at coordinate (250, 250). Step 3: Set your second super object with these properties: a) 25% chance of being a Zombie, 75% chance of being a Spaceship. b) 86% chance of appearing at coordinate (200, 200) and 14% chance of appearing at coordinate (-320, -240).	Step 1: Read the following scenario description: You are trying to get two items: an apple and a flower. The apple is beneath a tree and the flower is right next to a spaceship. However, if you try to touch the apple, a deer appears and destroys the flower. When you try to get the flower, a zombie appears and eats the apple. Step 2: Connect the provided nodes and complete the graph using entangler. Demonstrate the possible outcomes using the virtual character.

Table 2. Two tasks given to the participants in the user study.

A time-limited task was given at the end of each tutorial session. Table 2 shows the descriptions of the two tasks. We gave participants 10 minutes for each task and did not give them further instructions on how to complete the task. The task was based on what they had learned in each tutorial with a small challenge that required understanding of the system concepts to complete successfully. After the 10-minute limit, participants were allowed to ask for help if they were unable to complete the task. Participants were free to consult the tutorial during the task or ask for any clarifications regarding the entanglement concepts and visual programming interface functions introduced in the tutorials.

Post-study

After completing the two tasks, the participants were asked to fill out a post-study questionnaire about their experience learning and using EntanlgeVR. The questionnaire used a combination of standardized questions for usability [221] and our own questions evaluating learnability and support of creativity on a 7-point Likert scale (1 = Strongly Disagree, 7 =

Strongly Agree). We also conducted a one-on-one semi-structured interview at the end of the study that lasted about 15 minutes, to get more detailed feedback on the system and its use for creative purposes.

5.4.2.3 Data Collection

Data was collected through screen recordings of their shared screen as participants followed the tutorials and performed study related tasks. Additionally the semi-structured Zoom interview was recorded as were responses to the pre- and post-study questionnaires.

5.4.3 Results

All participants successfully programmed Task 1 (qubit + super objects + gates). 13 participants completed programming Task 2 (qubit + super objects + entanglement) within the 10-minute time limit. The remaining three participants completed Task 2 after receiving a hint from the researcher.

5.4.3.1 Questionnaire Responses

Post-study questionnaires are divided into three parts to separately evaluate: 1) usability 2) understanding of quantum entanglement concepts, and 3) support for easy creation of interactive VR scenes with entanglement concepts.

Usability

We used a System Usability Scale (SUS) [221] to measure the usability. Figure 36 shows separated results of positively worded items and negatively worded items based on the SUS

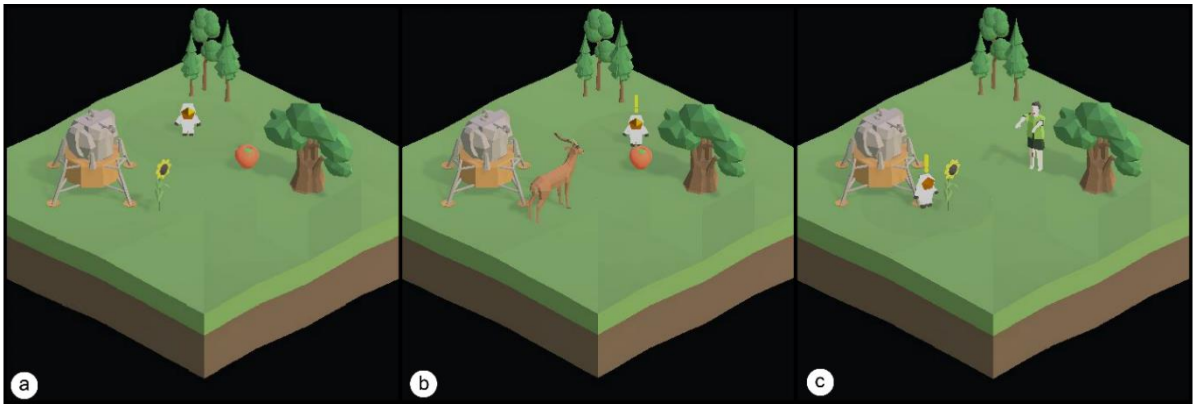
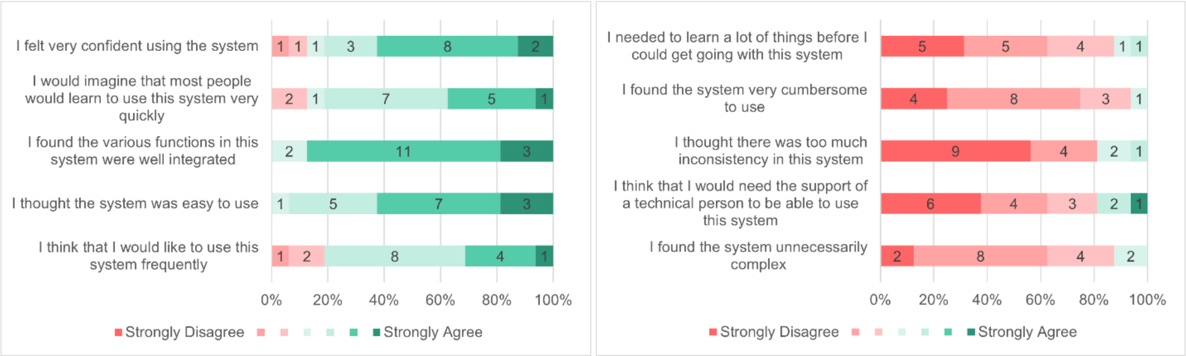


Figure 35. Visual results from Task 2 where participants were asked to create an interactive scene that has two different outcomes based on user interaction. Left: (a) shows the initial scene state that has two target objects, an apple and a flower, as described in the task description given to the participants. Middle: (b) shows one outcome if the user chooses to interact with the apple that causes a deer to walk out from behind the trees and eat the flower. Right: (c) shows another outcome if the user chooses to pick up the flower first which causes a zombie to walk out from behind the lunar module and eat the apple. Outcomes (b) and (c) were created by the participants using entangled relationships between these objects (apple, flower, zombie, deer), making a scenario where the apple and the flower cannot be taken by the user at the same time.

scoring strategy [222]. 15 out of 16 participants agreed that EntangleVR was easy to use. All participants agreed that the various functions were well integrated. As we used a 7-point Likert scale on SUS, we converted the SUS score to a range of 0 - 100 with a 1.67 point increment. The overall SUS score with a *M = 80.83* and *MAD* = 9.66 shows that our system has very good usability.

Understanding of Quantum Entanglement Concepts

Figure 37 (a) shows the results from questions related to understanding of quantum entanglement concepts. All 16 participants reported feeling positive (average score at 6.31) about learning the quantum concepts and about their interest in using these concepts for creative activities. They also all agreed that the system successfully demonstrated its capacity to teach users how to create virtual object behaviors and scenes using quantum concepts. Of



(a) *(b)*

Figure 36. Results of the System Usability Scale (SUS) questions. (a) shows questions 1, 3, 5, 7, and 9 (positively worded items). (b) shows questions 2, 4, 6, 8, 10 (negatively worded items)

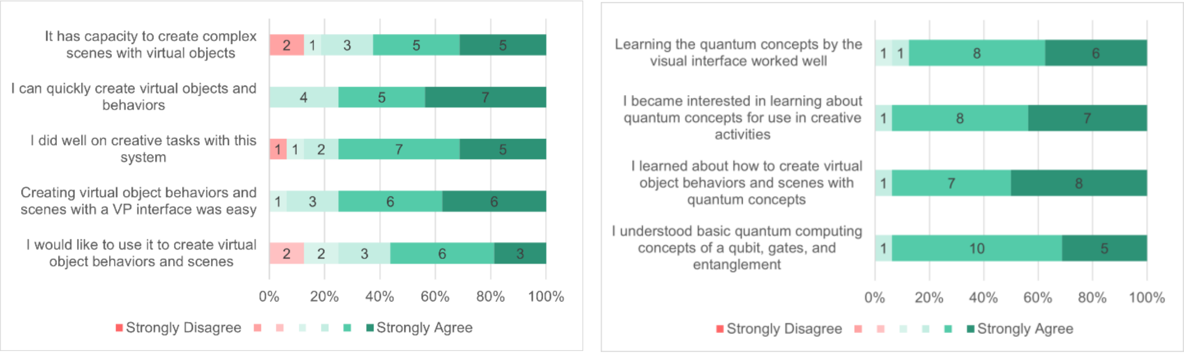
the 10 participants who had never taken any formal courses in quantum computing or quantum physics, all answered positively regarding their understanding of basic quantum concepts.

Support for Easy Creation of Interactive VR Scenes with Entanglement Concept

Figure 37 (b) shows the results from questions related to interactive virtual scene creation. All the participants responded positively (average score at 5.79) to the system enabling quick creation of virtual objects and interactive behaviors. 13 participants said they believed the system can be used to create complex scenes and virtual objects. 15 thought that creating with a visual programming interface was easy. 12 participants expressed desire and willingness to use the system to create virtual object behaviors and scenes.

5.4.3.2 Post-study Interviews

During the post-study interviews, we asked participants for feedback on the usefulness of the system, its weaknesses and their overall experience using it to create VR scenes, along with their thoughts on the application of entanglement for creativity. Interviews were transcribed



(a) *(b)*

Figure 37. (a) Results from questions related to participant understand of the use of quantum entanglement in the creation process. (b) Results from questions on system support for interactive VR scene creation.

by one researcher from the Zoom recordings and the text transcripts were exported for qualitative analysis. Screen recordings were matched with interview transcripts using the participants IDs. We employed an inductive thematic analysis approach [201] to the interview texts. Two researchers independently reviewed the transcripts and derived their own codes and descriptions of the codes from the conversation contents. A discussion between the two researchers was held to further examine and refine the codes and jointly arrived at a set of four themes that are presented below.

5.4.3.2.1 Enhanced program understanding from an easy and expressive interface

One of the most frequently mentioned positive features of EntangleVR was the ease of use. The reactive visual programming interface allowed outputs of different functions to be immediately visible in the preview window which helped the user understand the relationship between the super objects, entanglers and the corresponding outcomes. Ten participants mentioned that the expressive interface helped them understand and control the program design. Four participants reported that they did not face any difficulty during the entire learning and task completion process. At the same time, three participants pointed out that they are “not a fan of visual programming” (P0) or “not very used to visual programming” (P11) and would prefer a scripting interface, if available, for dealing with more customized or complicated needs.

P14: *“it's very easy to use because of the functionality and usability the interface gives me. I think it is the nature of visual programming environment. Click, drag and drop directly renders on the scene. It is easy to use and understand what I'm doing, and see the effects of the actual output. This was quite great.”*

5.4.3.2.2 Creation with entanglement and uncertainty

Participants found the idea of associating interactive scene creation with a set of probabilistic events “fresh and new”. More specifically, eight participants thought this method can be very useful to “simulate things that are very close to real life" (P2) or to “create a long drama of probabilistic chains of events or a choose-your-own-adventure story” (P8) or “a puzzle-like story” (P11). This is because the probabilistic nature of a qubit-drive super object in our system design is not just pure randomness, but something that is controllable with entanglement. P7 noted that “because you can change the probabilities and then the entanglement can be used to create or build relationship between objects, I think that is very useful in [creating] visual content.”

P2: *“The whole idea that allows to simulate virtual objects in quantum states is very interesting and figuring out how you can modify probabilities, let's say you can keep them random but still keeping their deterministic [behaviors], the concept of implementing these things that are close to real life was very fascinating.”*

Some concerns about creating interactive VR scenes with probability were also raised. P3 and P10 expressed doubts about quantum concepts by asking the researcher about the reasoning for creating probability using quantum amplitudes instead of using a classical probability generator. The researcher discussed the unfactorable nature of a shared state brought forth by entanglement and how such a state is hardly describable by classical probability which is based on the concept of statistical independence. Seven participants rated entanglement as relatively the hardest concept to understand but also the most powerful, although four of them simultaneously claimed that entanglement was not that difficult for them.

5.4.3.2.3 Diversity in creative activities

Participants pointed out a wide range of use cases like creating AR/VR narrative experiences, providing large variability in game character behavior and personality design, designing interactive media art installations where each user has a slightly different experience, using it to teach a few basic quantum concepts and to make music and soundscapes. Nine participants thought the system would be useful for making narrative based games. They talked about using entanglement for game design like “creating dungeon-like loops with random but controllable sections” (P9), “choice-based games” (P4), and “behavior design of game character” (P1). Three participants mentioned the system could be used by “digital artists who have some programming experiences” (P6) to create VR art installations. One participant explained the ability of the system to enable “diverse various non-deterministic visuals” as a reason for why artists would like using the system as it will “reduce effort and time to build virtual environments and interactions between characters and objects" (P14). One participant suggested using the system as a visual interface to an existing quantum computer.

5.4.3.2.4 *Learning support for basic quantum concepts*

Participants expressed that a system with expressive and interactive visual guides like ours can help people learn basic quantum concepts. While this is not the main goal of our prototype, users do need to understand the underlying concepts to be able to use the system to build interactive virtual scenes. Eight participants pointed out that students and beginner programmers unfamiliar with quantum concepts like qubit, quantum gate and entanglement could use the system in a learning environment (e.g. classroom). According to P6, the visual interface of the system was "fun and interesting that it simplified quantum concepts to be really digestible and approachable." P5 described the system as "a great way to introduce younger people and students in the classroom to dig into their creativity to make cool and compelling stuff." Four participants also mentioned that without prior-knowledge of quantum computing, entanglement may be a challenging concept for a first-time user, and it would become easier with more time spent using the system. On the other hand, participants who were familiar with quantum computing found the visualization of concepts through nodes and the preview window to be a helpful refresher.

P13: *"Before today, I have minimal knowledge, but after using the system, I now know some of the concepts of quantum computing."*

5.4.4 Discussion: Authoring Strategies for Creators and Storytellers

We have demonstrated how concepts from quantum computing can inspire the design of a visual programming interface for interactively creating virtual scenes that include relational objects and multiple outcomes driven by user interactions. From the results, we conclude that the use of the included quantum inspired concepts for creating interactive VR scenes was fairly successful with evidence showing that the EntangleVR prototype system provided an easy to use interface for engaging with complex interactive object relationships. We articulate four design strategies based on our interpretation of the data analysis and participant feedback and discuss our findings in this section. These strategies can serve as a guide for development and design of future authoring systems for creating interactive VR experience.

5.4.4.1 Clear Visual Indication of Possible Interaction Outcomes

One of the challenges in creating interactive narratives is that the creators may feel intimidated when designing interactions that may lead to multiple possible outcomes. As the choice of interaction made by the audience of the experience is uncertain, the creators after designing branching points that produce many different results may start to lose sense of control over how each interaction may contribute to the narrative outcome. Therefore, it is important to clearly inform them of the possibilities that may come out of each interaction at a branching point by the visual interface while at the same time letting them to test if the interaction correctly produces the expected effect. In our case, we visually display the probabilities for each super object as well as the possible outcomes of other entangled super objects on each observer node so that the creators can fully understand the impact brought each interaction. We also provided a test button on the observer node to simulate an interaction trigger to let them see the actual effect in the preview screen.

5.4.4.2 Provide Easy Walk-through for Testing Narrative Flow

As an interactive narrative may have multiple possible paths or sequences of events that one can choose to go through, the creator may need to quickly test out these possible paths to see if they are consistent with the narrative flow. Although the creator may embed random or probabilistic elements in a story or embrace a more procedural style of narrative development that it may not be possible to test out all the cases, a quick and responsive way to let the creator easily walk through various major narrative paths is still highly desired. In addition, game engines often provide play mode for the user to test the program, but it always starts at the very beginning of the experience. A customized starting point along with quick settings of object initial states can be helpful for the creator to run various test cases.

5.4.4.3 Consider Techniques for Creating Sense of Plausibility

Our participants were in general excited about using entanglement for the design of visual storytelling, interactive games, and digital art experiences. They were also able to propose extended usage of entanglement in interactive VR scene creation and suggested for more entanglement compatible object properties such as animation, sound, scale, and character behavior. They thought that entangling and associating different object properties together for interaction effects can lead to a real-life like dynamism in an interactive experience. It implies that the creators may want to provide the audience a sense of plausibility [223] in their interactive narrative to increase the realism of the experience they are authoring. Therefore, a future authoring system should consider how to help the creator build an experience with plausible interactions and narratives. From our study, we can observe that uncertainty and probability-driven events are also considered useful strategies to simulate the unexpectedness of real life and may help increase sense of plausibility. One participant specifically mentioned about the idea of using some probabilistic distribution function to simulate things in real life, which can be considered a further step to support plausible object behaviors.

5.4.4.4 Allow More Direct Manipulation

The idea of direct manipulation has been explored mainly in artists tool design for 2D visual art creation. Prior studies have shown that, for artists who are unfamiliar with programming concepts, manual manipulation and epistemic action on the target creation can help them better understand how the functions in the program behave [224, 225]. Similarly, for virtual object behavior programming, the creators may have a better understanding of their editing process if they can directly manipulate the object's interaction states while seeing a visual representation of perceivable changes reflecting their controls. In our work, we used a Bloch sphere to visualize the probabilities of a super object with sliders to control its state, in addition to numeric value control of its state. During our study, we noticed that participants with lesser programming experience much more appreciated the visual interface and the reactive outcome of slider control than those with greater programming experience. They asked for even more interactivity and direct manipulation of super objects such as drag and drop features to let them set more properties of objects in the scene. They also tend to rely more on the interactive preview feature to test out their editing on the probabilities of super objects instead of trusting the numeric value representation, although it does not mean that they do not need the numeric reference. In contrast, accurate numeric control is more desired by those with greater programming experience, and they expressed explicit preference for scripting interface over visual programming interface. Not surprisingly, they tend to use the input field on the interface to type in an exact numeric value for object state control instead of using a slider to roughly reach the desired state. Therefore, it is useful to keep both ways of object state control to accommodate creators of different programming levels while permitting more direct manipulation.

5.4.5 Limitations and Future Work

Our work provides an implementation of the concept of quantum entanglement as a new method for creating interactive virtual scenes. However, our work has some limitations. First, we could only perform a short-term study using a guided tutorial followed by simple tasks for every participant. Participants did not have enough time to fully explore and create their own virtual scenes using more combinations of features of the system. A long-term study enabling free form scene creation will be needed to see whether the study results still hold for both the system and the interface regarding support for creativity and easy creation of VR experiences. Second, since some of our participants (6 out of 16) had previous course experience in quantum physics or quantum computing, so their feedback and learning experience was different from those who did not have prior knowledge. Besides that, because our simplified application of entanglement does not involve an explanation of the qubit phase or the underlying mathematics, it led to some questions regarding the difference between quantum amplitudes and classical probability. While this does not present any issues when using the system to create interactive virtual scenes, the difference needs to be highlighted if the system is used in a classroom teaching environment as a simple introduction to a quantum way of thinking. A future study of two larger groups of users: with and without prior quantum knowledge, may reveal newer aspects of learnability and education use of our system. Lastly, while EntangleVR has an expressive interface for interactive VR scene creation, our system can be expanded with more integration with the classical features, though beyond the scope of this paper, which could help make the system more powerful.

Our main focus in this work is the exploration of the possibility of making interactive VR scene creation easier by using the idea of quantum entanglement and to demonstrate that EntangleVR is capable of allowing beginner users to build relatively complex and relational virtual scenes of multiple outcomes. In the future, we plan to continue exploring entanglement at different scene creation scales (e.g., procedural scene generation, multi-scene entanglement).

5.4.6 Summary

In this paper we presented a preliminary evaluation of EntangleVR, a visual programming interface to build interactive VR scenes that have multiple outcomes determined by user interactions. To enable the connection between user interaction and scene narrative outcomes, we borrowed the idea of quantum entanglement to simplify the design of complex inter-object relationships. We conducted a preliminary user study with 16 participants to determine if our system is capable of supporting creativity and easy creation of interactive VR experiences. Our results indicate that all participants were very positive and excited about using the concept of entanglement in the interactive VR scene creation process. Many of the participants who did not have much knowledge about quantum entanglement before the user study appreciated learning the basic quantum computing concept after using our system. Participants also commented that EntangleVR is a very “futuristic approach” for VR scene creation based on top of potent and highly promising quantum inspired concepts.

5.5 Conclusion

In this chapter, I demonstrated how introducing new relations into the storytelling process may help the creators tell new stories and produce more engaging experiences for the audience. By designing novel workflows to enable immersive scene creation that contain relational elements, our work allows creators to easily tell stories that can unfold in an interactive manner. In addition to incorporating relations as a narrative element in storytelling, we also explored the possibility of connecting creators together to enable a more collaborative authoring process. This approach well extends from the existing user-centered content generation practice of social media into an immersive domain, and points out a possible future of storytelling driven by community synergy. The users, as both creators and consumers, will be able to intra-actively work together to produce new stories, while immersing into each other’s story worlds with a high level of presence and embodiment. If we consider the benefits of immersive storytelling include a stronger sense of empathy, then we will for sure be able to build up stronger social ties and communities by empowering more creators of relational stories.

6. CONNECTVR AUTHORING SYSTEM

In Chapter 5, we explored and validated the idea of relational storytelling that incorporating new relations into a storytelling process can possibly lead to new forms of immersive narrative experiences. However, real life is a lot more complex composed of many interweaved relations and actions that are not as simple as “if A then B”. Many seemingly unrelated things may turn out to be deeply interacting or intra-acting with each other by the mediation of many invisible actors. When we look at human history, we see butterfly effects [17] that a minor and careless action may project a huge impact on many other things. It may develop into a sequence of events, each of which may take place one after another and even resonate with each other to formulate a long-lasting loop.

In EntangleVR, we discussed our findings that creators are interested in inducing a sense of plausibility in their narrative design by introducing some random and unexpected events to simulate the unpredictability of life. Similarly, a large network of interacting objects that displays a level of emergence or a long sequence of events that makes it hard to foresee the final outcome may also be used as a strategy to induce such a sense of plausibility. The idea behind such strategies is simple – life is random but not completely random. If we carefully look at the historical trajectory of certain events, we can see a reasonable development of events driven by cause and effect. Therefore, as creators, we will try to approximate this complexity with a similar cause-effect trajectory, so that we may induce a sense of plausibility for the audience in a virtual storytelling experience.

Figure 38. Our code-free visual programming interface focuses on authoring narratives driven by a series of cause-effect relationships triggered by the user's actions. The example here shows story events that are initiated by the user. Left: (a) the user (low poly avatar) typed “I am hungry” in the text input field to talk with the virtual character in black. The virtual non-player character (NPC) responds to the user and starts cooking food. Middle: (b) continued from (a), the NPC character's cooking causes a huge fire, and burns down the area. Right: (c) the burn leads to zombies emerging which the user accidentally disturbs causing them to chase the user.

To achieve this goal, I present a new authoring system ConnectVR in this chapter. Taking insights from EntangleVR and SceneAR, ConnectVR approaches immersive storytelling from a pure relationist view where creators can describe virtual agents as individual actants in an immersive environment simply by their possible interactive actions. Focusing on enabling complex relations between these actants, I propose a simple yet efficient VR authoring workflow that can be used for the design of a wide range of interactive behaviors in a virtual reality that involves complex relations. Targeting creators of limited technical experience or knowledge, this new workflow does not introduce any complex algorithm-like computational thinking or paradigm like EntangleVR. In this way, we can truly let the creators to think like a human instead of like a computer so that they can focus on designing the phenomenal aspect of a virtual environment without spending too much time learning and implementing on the technical aspect. More natural and creative interaction design, therefore, becomes possible for them during their production of VR narratives, even if they do not have any technical knowledge or help from professional programmers.

6.1 Introduction

Interactive narrative design has been widely explored since the emergence of interactive fiction (IF) in the 1970s followed by hypertext fiction in the 1990s. With simple input methods such as text commands or mouse clicks, users can control story characters and engage with fictional worlds such as exploring the ruined underground empire in Zork [226] or playing the role of a palace minister in a renaissance style society in Varicella [227]. More recently, demand for interactive narratives with expressive visuals has seen a growth with increasing popularity of video gaming [228, 229] and virtual reality (VR). This increased demand coupled with recently introduced technologies presents an opportunity to create new types of interactive fiction that allows users to engage with the virtual world and narrative from a first person perspective, both, immersively in VR and in 3D, on a computer.

In many IF stories, such as Galatea [230], Façade [231] or A Dark Room [232], the user interacts with virtual characters using a combination of actions commands such as *look, give, approach, build* or natural language via text input. For example, in A Dark Room, the singular action of *stoke fire* has various direct consequences depending on where in the narrative that action is taken (e.g., wood store depletes, a wanderer knocks at the door, some animals approach). The action leads to subsequent appropriate actions becoming available to the user (e.g., investigate, turn wanderer away, build a trap). With a combination of actions (user clicks on them to trigger the action) and consequences that are communicated to the user via text descriptions, the narrative can progress differently for each user.

These part-game part-story systems are capable of handling user input, assembling the narrative from an array of pre-scripted story fragments, and making everything fit together to create a coherent narrative experience that has the potential to be unique for each user. In a 3D environment, users can similarly be offered opportunities to interact with the virtual world, but the story fragments need to have more specific and detailed representations in the form of actions, behaviors and movements for both the user and the story characters, along with audio-visual feedback. Thus, authoring interactive fiction in 3D would require building explicit causal connections between events and objects along with corresponding visual and spatial representations of outcomes as opposed to text descriptions used in traditional IF. Existing development methods for creating interactive narratives in 3D and VR are largely adhoc. They either follow game development practices which are not well aligned with the purposes of narratology [229, 233], or only focus on text-based dialogues for characters without providing support for designing the entire experience [234, 235, 236]. Building cause-effect relationships between user actions and virtual entity behaviors requires substantial programming experience and expert domain knowledge such as familiarity with plot graph construction using logic operators or implementation of AI planning algorithms. Creators such as artists, writers, and storytellers, who may not have the requisite technical skills, are often at a disadvantage with limited options available to them to create interactive narratives in 3D.

In this chapter, we present ConnectVR, a visual interface to enable non-technical creators to design 3D narrative experiences. Our code-free authoring method specifically focuses on the **design of narratives driven by a series of cause-effect relationships** (e.g., butterfly effect) triggered by the user's actions. In addition to creating the narrative, our interface allows realtime visualizations to ease debugging and support fine tuning. Imagine the following scenario where a user is camping in a wooded area and can perform activities such as lighting a campfire, cooking food or firing a gunshot. Reasonable explicit outcomes of these actions could be nearby animals fleeing at the sound of the gunshot or the same animals approaching the camp enticed by the smell of food. A less explicit possible outcome could be the user accidentally starting a forest fire that forces the animals to run and escape. As seen above, user activities can cause both direct and indirect effects on the surrounding virtual agents and the environment, leading to different permutations of story outcomes. To build such a scenario, instead of creating a discrete set of choices and hard coding all possible outcomes [237], a creator can easily build the cause-effect connections between the actions and the agents using nodes in our visual interface.

Behind our visual authoring interface is a relational graph composed of action definitions that allow for causal and temporal relationships to be created between the user's actions and virtual agent behaviors. Figure 38 shows an example story scenario enabled by our authoring system.

The main contributions of our work are as follows:

- A new relational graph-based method that centers around action, causality, spatial and temporal patterns as the authoring guides for non-technical creators of 3D interactive fiction experiences.
- A visual programming interface, workflow and real-time visualization system to support fast and easy code-free creation of 3D narratives with complex inter-object relationships.
- Results from a workshop with 15 participants from artistic backgrounds demonstrating usability benefits and creativity support.

6.2 Related Work

ConnectVR is inspired by prior work in development tools for interactive fiction and narrative games, computational narrative methods, and visual programming for creativity.

6.2.1 Development Tools for Interactive Content

There are a number of development systems or programming languages dedicated to creating IF such as Inform 7 [238], ink [234], and Twine [239]. Inform 7 is a programming language and an authoring environment targeted at writers and specifically designed for creating IF. It allows writers to use natural language statements to create text and image based stories with different levels of complexity. Ink is a markup scripting language for non-technical writers to create choice-based interactive stories. Other than these tools, automatic story generation is another active area of research. These systems focus on information generation and computational creativity where artificial intelligence (AI) [240, 241] and psychological models [242, 243] mimicking human behavior are often explored [244]. However, most of these fully automatic approaches are not yet integrated into the development process of actual interactive narratives. AskBERT [245] is an AI-based text-world generator that automatically constructs a playable IF world based on the plot of a book using trained thematic commonsense from other similar stories. While it works well for limited use cases, it is not open ended enough to allow for creator input and creativity.

Video game stories and VR stories, on the other hand, have more requirements for specific hardware device support and realtime graphics. These stories are often created using a game development pipeline created using engines such as Unity [211] or Unreal [212]. However, game engine workflows are often complex for non-technical creators and require software engineering skills and programming experience.

A number of systems have been specifically proposed to aid the development of interactive game narratives such as Expressionist [236], StoryAssembler [235], IFDBMaker [246], StoryPlaces [247], Ensemble Engine [248], Comme il Faut [249], and Villanelle [250]. However, similar to the tools available for IF creators, these tools also do not provide an integrated solution or full pipeline that non-technical creators can easily use to build their own narratives. For example, Expressionist is a web-based in-game text generation tool that can help generate descriptive texts for virtual objects based on attribute tags and character dialogues and conversations. The Ensemble Engine is a visual authoring tool that can help define and simulate social factors that impact virtual character relationships and their motivations using scored rules. Villanelle proposed a blockly-based programming language [251] to simulate autonomous character behaviors.

Taking inspiration from Twine, ConnectVR simplifies the complex game development workflow by avoiding the use of any scripting languages that were required in prior works. Non-technical creators can independently create interactive narratives in 3D using a code-free visual interface for composing complex relationships and behaviors. To support meaningful interactions in a story, in addition to what previous tools enable, our system allows the creation of actions driven by a variety of user inputs, including text commands, mouse clicks, VR or game controller events, as well as natural body gestures in VR and 3D such as position and movement in space, gaze and touch. The wide variety of input methods allows for flexibility in developing for both desktop and immersive environments.

6.2.2 Computational Narrative System

Building an interactive narrative system that facilitates meaningful selection of narrative events based on user interaction is a challenge [252]. Many prior works have been focused on plan-based narrative generation methods and have proposed various interactive system designs that take factors such as character personality [253, 254], dilemma [255], social relationships [256], intent [257], task hierarchy [258, 259], and authorial goals [260], to model logical and coherent narratives [261, 252]. For example, Goal Oriented Action Planning (GOAP) is a decision making architecture widely used in video games to help NPC characters plan and adjust their behaviors to reach preset goals defined by the author [253, 262]. Interactive Behavior Tree (IBT) extends upon the Behavior Tree [263] formalism's advantage in authoring branching narratives to handle free-form user interaction in the story [264, 265]. Intent-Driven Partial Order Causal Link (IPOCL) is a search planning algorithm that reasons about character intention and possible goals to create causally sound plot structures [257]. Riedl and Young categorized the design of interactive narrative system into two types: simulation-based and deliberative [261]. Simulation-based system employ decentralized agents of independent decision-making model to behave autonomously in response to the dynamic story world. Deliberative system monitors the entire story world and finds the best solution of selecting the next sequence of actions for all characters based on specific constraints.

However, the complexity in the specification of these systems can hardly be translated into an easy authoring process for non-expert users, as it requires specific domain knowledge such as writing Planning Domain Definition Language [266] or plotting behavior trees with logical operators [267]. With a goal to minimize the learning curve, we propose the usage of a relational graph to guide cause-effect relationships between the user and virtual agents' behaviors, without requiring the creators to have any domain knowledge or understanding of logic operators. We take a simulation-based approach that enables each virtual agent to have their own actions that can be triggered by user behaviors. Creators can also design highly detailed and temporally ordered execution commands inside each action so that an arbitrary sequence of agent behaviors can be implemented to meet the creators' specific narrative requirements.

6.2.3 Visual Programming for Creativity

Visual programming systems are often designed for users with beginner level programming knowledge [268]. The use of graphical elements to compose a program visually is well-suited for learning difficult concepts or doing creative computing tasks [269]. Scratch [270], for example, provides visual blocks to support easy creation of 2D animated stories and is widely used in K-12 educational settings to promote creativity and learning [271]. Blockly [251] is a toolkit that supports creation of domain-specific visual programming language and has been used in various creative projects [272]. Many content creation coding platforms (e.g., Unreal, Unity) and software have integrated visual programming interfaces specifically to enable artists and designers to engage in creative computational tasks. Visual programming tools are also widely used in various creative industries such as film production [273], music [220], game design [212], architecture [274] and multimedia art [275, 276].

In the domain of interactive narratives, a plot graph is often used to manage all possible narrative trajectories [277]. TWINE [239] provides a visual graph system to let storytellers easily write branching plots for their choose-your-own-adventure stories. Deig [278] is a visual prototyping tool for making point-and-click adventure game narratives. Narrative Threads

[279] is another toolkit with a visual diagramming interface to support the creation of narrative-based games.

ConnectVR provides a node-based visual graph interface to help creators construct cause-effect relationships between user and virtual agent actions. ConnectVR includes a block-based imperative programming panel inspired by Scratch's [270] interface to enable the creator to program details for each action node created using the graph interface. Combining both allows ConnectVR to offer seamless transition between high-level narrative planning and low-level behavior programming in the same visual interface, unlike existing tools and prior work. Our system also provides real-time visualization of programmed agent actions to further accelerate the authoring process for creators.

6.3 System Design

6.3.1 Design Goals

We built ConnectVR as a plugin for the Unity game engine with a custom visual programming interface and authoring panels to support fast and easy code-free creation of 3D narratives. Our system specifically focuses on creating narratives driven by a series of cause-effect relationships between a user's actions and corresponding virtual agent behaviors. Our main aim is to enable non-technical creators to design narrative experiences where the consequences of a user's actions are persistent and impact the user's experience of the narrative. In this work, we refer our authoring system targeting users as creators (e.g., artists, designers or storytellers) and the VR narrative experience end-users or consumers as users. Specifically we have three design goals for ConnectVR system:

- To flatten the learning curve and effort required to design 3D narratives based on user action and related virtual agent behaviors.
- To raise the ceiling of the expressiveness of authoring tools for 3D interactive narratives.
- To help creators use a variety of input methods (keyboard, mouse, VR controller) in 3D and in VR that are most appropriate for the actions they design.

6.3.2 Block-based Model

ConnectVR is based on the idea that a 3D story world is populated by a user (the person experiencing the narrative), various virtual agents (e.g., characters, mobile scene objects like cars or animals) and multiple static entities (e.g., trees, buildings, terrain). We adopt an action-based model to represent the narrative plot -- the user and the agents are capable of performing certain actions and each action has potential consequences which can trigger further actions. The creator's task is to design and create these actions, and determine each action's causal, temporal and spatial relationships to the user and the virtual agents. The user's interactive experience is then composed of sets of actions initialized and executed based on the choices the user makes as they go through the narrative. Figure 39 shows the workflow for creating a

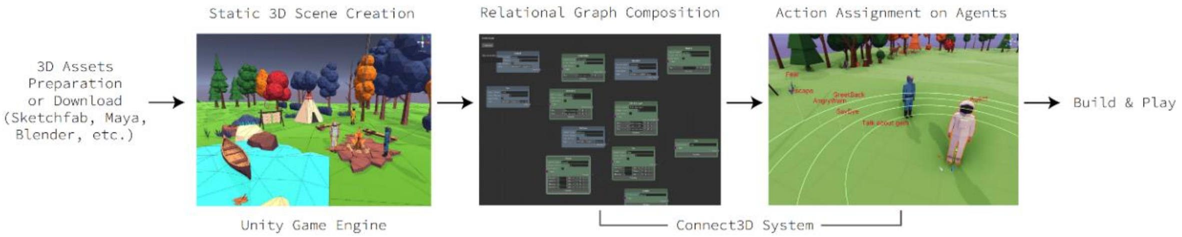


Figure 39. Overview of the authoring workflow using our ConnectVR plugin in the Unity Game Engine. After setting up a static 3D scene, a relational graph composed of actions and relationships allows creators to design and assign actions to the virtual agents in the 3D scene.

simple interactive narrative experience. Figure 40 shows an example of how an interactive story world is structured. We use a *relational graph* to support our action-based method of creating narratives. A relational graph contains two main elements:1) actions, and 2) causal links.

6.3.3 Action Unit

Action refers to the mimetic activity in a story world [280, 281]. We use an action as the basic narrative element in ConnectVR that represents a behavior-based plot fragment. The creator defines each action as an abstraction for what the user's character or an agent behaves in a defined way. For example, an agent's Cook action involves a series of animated events such as moving to the kettle and starting a fire. A human user's natural behavior of Look in VR serves as an input condition for a LookAt action node running. Each action has the following parameters:

- **Impact Radius**, which controls how far the effect of an action reaches in 3D space described as a sphere of radius *x*. The range is centered at the position of the agent or the user who performs this action.
- **Action Type**, which can either be a *user action* or an *agent action* specified by the creator using a checkbox. We use action type to differentiate between user input driven behaviors and agent's programmed behaviors.
- **Execution Block**, which contains the implementation details of a defined action related to how the action is shown and performed by the user or an agent in the virtual world. For user actions, the execution block requires the specification of an input method the user will use to initiate that action. For example, the user may need to type a pre-defined

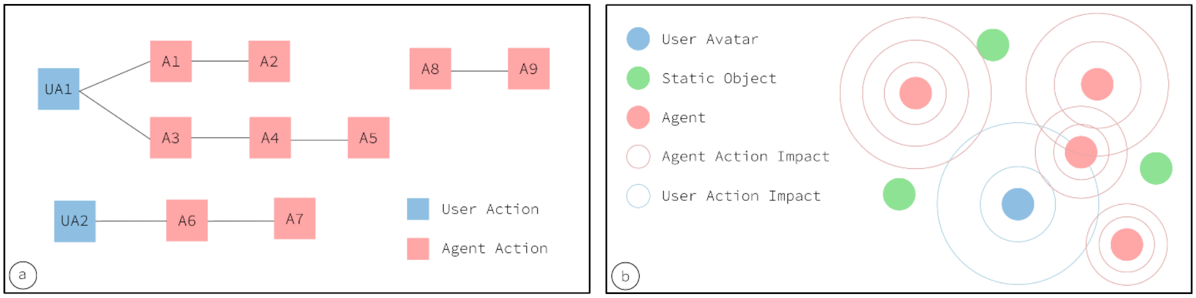


Figure 40. An example of how an interactive narrative is structured in the ConnectVR system. Left: (a) shows a relational graph defining how user actions and agent actions are linked to form the cause-effect relationships. Right: (b) shows a story world populated by a user's avatar and virtual entities (agents and static objects) with the action impact radius defined in the relational graph. The number of action impact circles depends on the number of assigned actions to the user or the agent.

command such as “hello” in the text input field during the story play mode to activate a specific action. For agent actions, the execution block contains a list of commands that can be executed by the agent. For example, suppose a virtual character is designed to perform the *greet action*. This action may be triggered by a user typing “hello” or “hi” causing the virtual character to follow a sequence of creator programmed commands in the execution block: turn towards the user → step forward → say “hello there.”

6.3.4 Causal Link

A causal link refers to the cause-effect relationship between two actions, considered critical in supporting the coherence and logic in a story [282]. Our method for causality builds upon a simple idea: every action can have multiple consequences which can trigger subsequent actions leading to further consequences and so on. In our system, a causal link relates the effect of one trigger action to the pre-condition of a consequent action. Therefore, each action can have: 1) a list of trigger actions which temporally occur before this action, 2) a list of consequent actions which occur due to and after this action. Note that for a user action, the trigger action is a user input event, which is detected during the story play mode. Figure 41 shows an example of how actions are represented and linked using our visual interface.

6.3.5 Input Methods for User Actions

To support natural interactions in a story, creators often need to connect user input events to narrative events. Our system supports three types of user input:

- **Device-based input**, which includes hardware input methods such as mouse click, keyboard keypress, and VR controller button-press.
- **Verbal intent-based input**, which is based upon the user's verbal speech content taken from either microphone or typing in the chat-box (provided by our system on the main interface). We implemented and pre-trained a Multinomial Naive Bayes Classifier [283] using UnityNLP library[12] to parse the main intended topic from the speech content. The pre-trained topics include greeting, ask for location, ask for name, expel, apology, gratitude, etc. The creator can also define their own keyword set to use as custom condition for the action input. We also provide "anything" as a wild card to let any verbal input become valid condition for a user action.
- **Gesture-based input**, which is based on user body movement such as look at, pick up, touch, move toward, move, nearby, standby, etc. Whenever the user in VR performs such body movement, they may trigger a user action conditioned by the movement.

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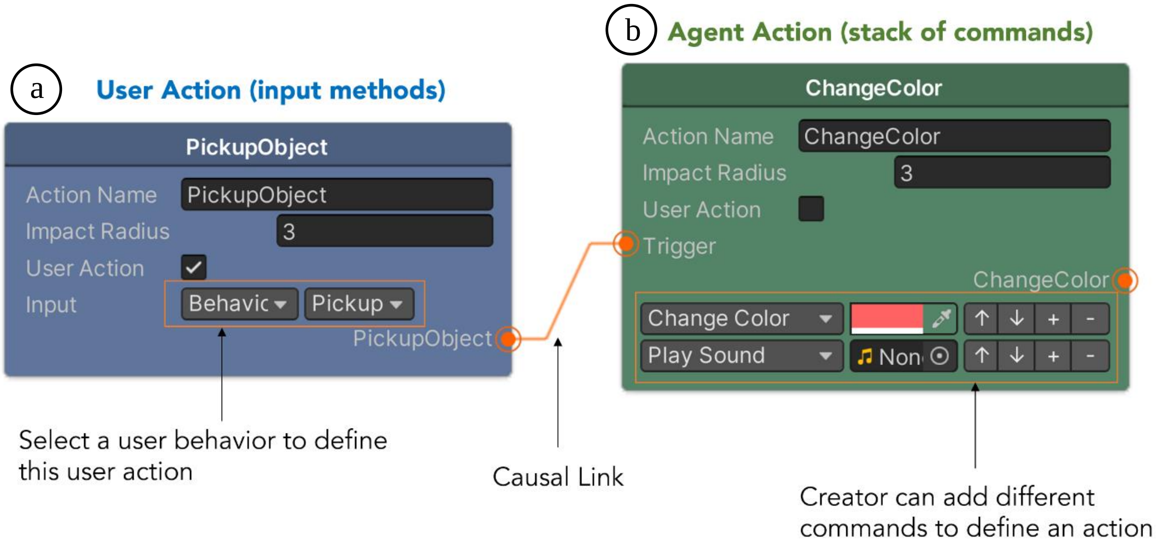
[12] https://github.com/voxell-tech/UnityNLP



Action Name PickupObject
Impact Radius 3
User Action ☑
Input Behavic Pickup
PickupObject

Action Name ChangeColor
Impact Radius 3
User Action ☐
Trigger
ChangeColor
Change Color ↑ ↓ + -
Play Sound Non ↑ ↓ + -

Select a user behavior to define this user action

Causal Link

Creator can add different commands to define an action

Figure 41. An example of how actions are represented and linked using the ConnectVR visual interface. Left: (a) a user action is represented as a blue colored node. It does not have an input node port on the left edge but the creator can specify an input method to be set as a condition to activate this action. The example action in the figure is set by the behavior pattern “pickup”. Right: (b) an agent action node is represented as a green colored node with both input (left edge of the node) and output ports (right edge of the node) that take causal links. The example the node here has (i) an execution block composed of two commands: change color to red → play a sound clip. Because the user node and the agent node are connected, this agent action will be triggered when the user pick up the agent.

All these input methods can be defined in the user action node and be used as triggers for other agent actions (Figure 41). These input methods can be specified in the execution block of the user action node as a condition for this action to activate and trigger other consequent actions. During story play mode, when a user input event matches with any of the creator-specified input conditions of the user action nodes, the corresponding user action will be activated. Figure 42 shows an example of how user actions are driven by user input events.

6.3.6 Agent Action Commands

We divide agent action commands into six different categories:

- **Spatial control**, which includes space and transform related commands such as Move, Follow, Rotate, Scale, etc.
- **Visual control**, which includes graphics and rendering related commands such as Color change, VFX activation, Transparency change, Appear / Disappear, etc.
- **Temporal control**, which includes time related commands such as Wait, Instant trigger (immediately cause the consequent action on other nearby agents to play before executing the rest of the commands in the execution stack), etc.
- **Auditory control**, which includes audio or speech related command such as Play sound clip, Speak a sentence (the creator can provide custom sentence content and the virtual agent will speak it out by real-time voice synthesis enabled by Microsoft Azure speech service [284]), etc.
- **Animation control**, which includes animation related commands such as Play animation clip, Reset, etc.
- **Utility control**, which includes general state control of the agent such as Activate / Deactivate agent, Custom state set, Custom function call, etc.

All these commands can be mixed and stacked with each other to constitute a custom agent action. There is no limit of how many commands one action unit can take.

6.3.7 Relational Play

A story may involve different types of cause-effect relationships [282], such as physical consequences in a virtual environment (e.g., lighting a camp fire near a tree can cause a forest fire), arbitrary narrative development (e.g., a user must be at a specific location to proceed through the story), or social dynamics (e.g., an agent gets influenced by another panicked agent

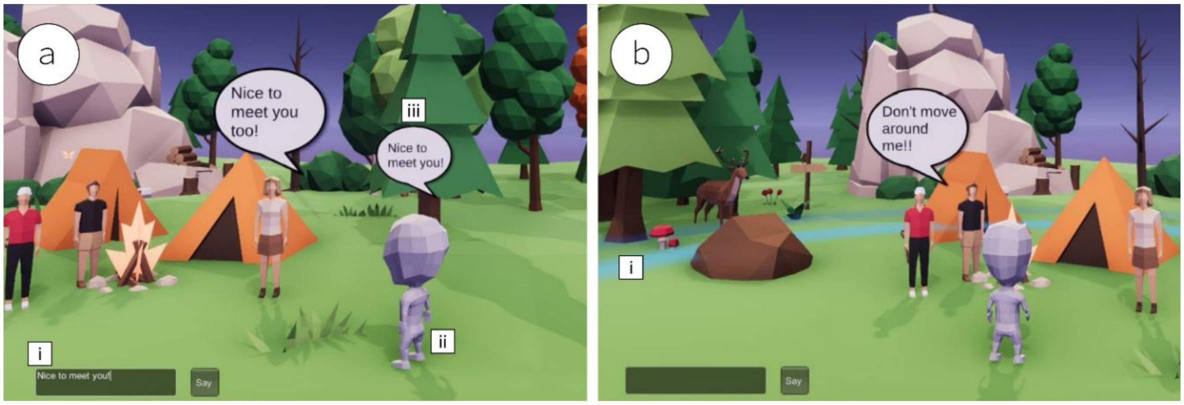


Figure 42. An example showing user actions driven by user input events. Left: (a) the user types "Nice to meet you!" in (i) the text input field, (ii) the user's avatar can optionally repeat the typed text by TTS, and (iii) a speech bubble with the same text appears above the avatar's head. If the parsed intent from the typed text matches a creator-specified verbal intent condition on a user action, then that action is activated, and may trigger an agent action on a nearby agent as a response to what the user just said. Right: (b) user moves around in the virtual space and (i) a large blue-colored ring effect appears on the ground indicating successful activation of a valid user action. This user action can then trigger a consequent agent action, for example, on the virtual agent in red shirt causing it to respond to the user's movement behavior.

nearby and feels scared). In our system, there are no restrictions about how a creator can design and build these cause-effect relationships in between different actions. Figure 43 shows a set of examples of possible ways to design relations by the creators using our system. Just like real life, an action may lead to multiple other actions, or multiple actions may end up at the same result action. The creator may also design an action chain of any length to simulate chained reactions. Feedback loop is also possible that an action can be the cause of its causal action. Lastly, an action can be the causal action of itself to simulate a spreading effects such as fire, wave, or virus.

6.3.8 Spatiotemporal Constraints

Our system enables creators to design many kinds of relationships connecting the actions by a causal link, but a causal link does not guarantee the trigger of a consequent action when the causal action is activated. It has to be modulated by spatial and temporal factors, which are the positions and availabilities of agents as well as the impact radius of each action that determines how far this action may reach other agents. Figure 40 (b) shows a conceptual spatial map with a user and virtual agents, each with their own impact radius for the actions they can perform. When an agent or a user is performing an action, the effect of this action is only valid within a spherical radius around it. If no other agent is nearby, then the action does not lead to any consequences. Increasing the impact radius can ensure consequent actions but it may also lower the plausibility of the cause-effect relationship in some cases (e.g., a spoken word can be heard by an agent far away from the user). Figure 44 shows an example of how spatially constrained cause-effect relationships may affect the narrative experience. After the trigger of an action on an agent, there is also a customizable cool-down timer on this agent to prevent it from performing the same action again. The creator can individually control each agent to determine how often they would like to see the agent play an action. In this way, some action may only happen once while some other actions may take place multiple times with a waiting interval between each play.

6.3.9 Action Assignment

For purposes of re-usability, an agent action is designed as a capability that can be assigned to multiple virtual agents. The definition of a virtual agent is not limited to a virtual character but can also be any virtual entity (a tree, a furniture, etc.). Therefore, an action can also be a representation of an object's state change (e.g., start burning, gradually deteriorate), depending on how its execution block is programmed. Each virtual agent can have any number of agent actions, and the more actions the virtual agent has, the more interactive it may appear to the

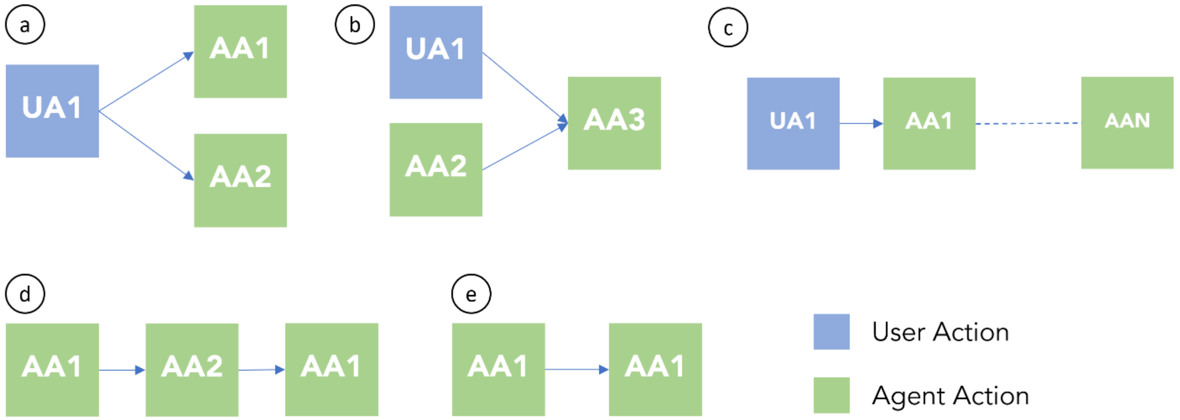


Figure 43. Examples of possible relational play by the creator. (a) one action may lead to multiple other actions. (b) multiple different actions may lead to the same result action. (c) an action chain can be made of any length to formulate chained reactions. (d) an action can be the cause of its causal action to formulate a feedback loop. (e) an action can be the causal action of itself to formulate a spreading effect.

user in different situations. The creator can drag and drop ConnectVR's agent action script on to any 3D object in Unity's scene composer to convert them into interactable agents. We provide custom interface support to automatically visualize the impact radius of each action assigned to an agent. This allows the creator to easily determine and estimate the likelihood of an agent's action to trigger a consequent action on another agent.

6.4 Implementation Details

To maximize the compatibility with existing processes for authoring 3D interactive narratives and to provide easy access to our development environment, we built ConnectVR as a plugin for the Unity game engine. Our node-based visual programming interface is supported by the xNode library [285]. For user and agent actions involving speaking, we use the Klattersynth TTS engine [286] for offline voice synthesis as well as Microsoft Azure’s speech service [284] for cloud-based voice synthesis.

6.4.1 Authoring Support and Graph Navigation

Managing a large narrative project can be an overwhelming task. Although the graph canvas is designed as an infinitely draggable grid, as the number of action nodes increases, creators will need to move across the grid more frequently to work on different parts of the graph to compose complex chained relationships. To help the creator quickly create and navigate between action nodes, we provide an action search function. Searching by action name and clicking on the desired result causes the graph to center on the target node position on the canvas. During the authoring process, upon creation of an action node, the creator can give this action a natural name (e.g., a verb or a short phrase) or follow their own naming convention. There is no restriction on the names but if a newly created action name is already taken by an existing node, the system will automatically identify duplicates and treat the new action as a short cut node referencing the existing node. A short cut node will not display any editable fields to avoid action definition conflicts. Short cut nodes can also be used to help organize the wiring of cause-effect relationships and ease the effort in creating nodes that require connections with a large number of other nodes.

6.4.2 Automatic Sequencing and Temporal Control

A story world may contain many autonomous agent behaviors that do not need to be driven by the user. Our system enables creators to define agent behaviors that unfold over time without user intervention by assigning an initial action to the agent. The agent that has an initial action will immediately start this action when the story play mode starts. Use of commands such as *Wait* and *Trigger* in the execution block can provide temporal control for such actions. A *Wait* command allows the creator to define actions that have long sequences of commands with

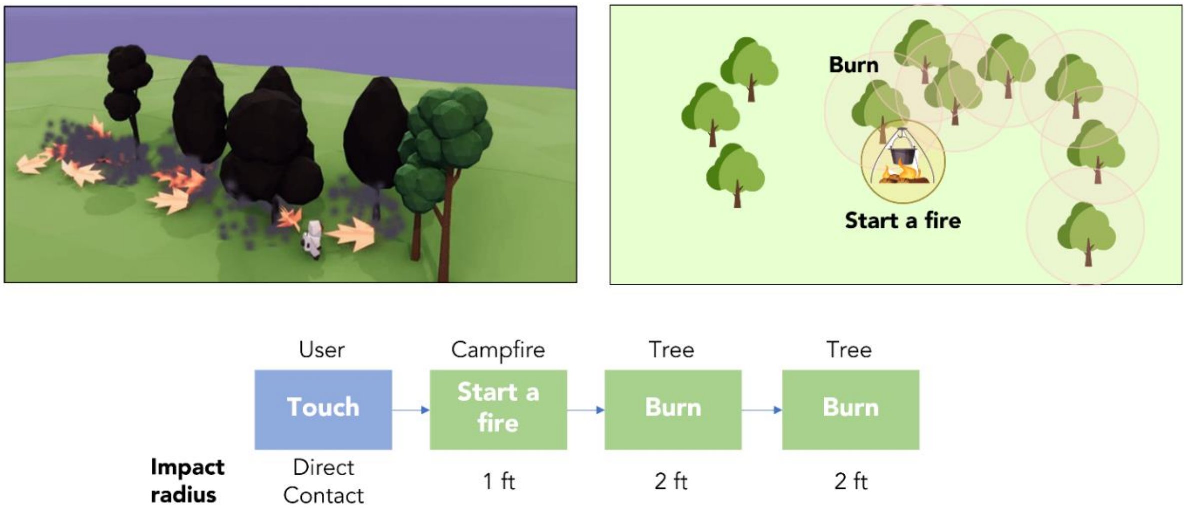


Figure 44. An example of how spatially constrained cause-effect relationships may affect the narrative experience. Top-left: a scenario where the user accidentally burned down the entire wood area. Bottom: a set of actions that lead to a fire in the wood. The user starts with a "touch" action on a campfire to cause the campfire object to "start a fire". After "start a fire" action is activated, as long as there is a true object capable of "burn" action within the campfire's 1 ft impact radius, the "burn" action will be triggered. Similarly, this "burn" action may trigger other tree objects' "burn" action if they are within this tree's 2ft impact radius as defined for "burn" action. Top-right: a simple spatial map showing the location of different agents as well as the impact radius of each action. A sequence of "burn" becomes possible when the trees are arranged nearby each other following the initial "start a fire" by the campfire.

timed behaviors. For example, a Travel action can be defined with a sequence of commands as such: move to location A → wait for *X* seconds → move to location B → wait for *Y* seconds → move to Home. A *Trigger* command can further enable more complex cause-effect relationships by forcing consequent actions (if available) to happen before the completion of the execution block. When the *Wait* command is used in combination with a *Trigger* command, an action that is supposed to happen before its consequent action can be delayed until or after the consequence, creating an effect that looks like a violation of cause-effect. This type of relationship can help the creators author agent behaviors with logical flow but without the presence of explicit cause-effect relationships, creating mystical plots often seen in suspense fiction.

6.5 Workshop Evaluation

We conducted a workshop study with 15 participants to understand if our prototype meets our design goals. We specifically designed our evaluation to, 1) see if participants were able to use our visual programming interface to construct cause-effect relationships between user actions and virtual entity behaviors, 2) see if participants were able to create a variety of original 3D interactive short narrative experiences demonstrating expressiveness of our system, and 3) gain insights into the usability and ease of authoring narrative experiences with our code-free system. Before the workshop, we conducted a pilot workshop with three participants to get early feedback on ConnectVR's user interface and functionality to help us identify and fix technical and user experience issues.

6.5.1 Participants

We recruited 15 participants (5 female, 9 male, 1 undisclosed, age range 18-44) to evaluate our system. Since ConnectVR is designed for the creative community such as artists, storytellers and writers, we looked for participants with a particular interest or prior experience in interactive narrative and 3D content creation. Participants were from backgrounds including media arts (9), computer science (3), film (2), and communication (1). All participants had different levels of experience with 3D modeling as well as creating interactive experiences in VR and in 3D.

A 5-point Likert scale was used for all ratings (1 = not at all, 5 = A great deal). Participants rated an average of 2.86 regarding their familiarity with creating 3D models or 3D scenes. Blender was the most common 3D modeling software reported (6/15 participants). Participants rated an average of 2.6 regarding their familiarity with creating interactive VR experiences.

They also rated an average of 3.3 on familiarity with creating interactive 3D experiences. Unity was the most common 3D experience development tool reported (6/15 participants). On visual programming, participants rated an average of 2.73 with Max/MSP as the most common visual programming language reported (6/15 participants). On average, participants rated 3.8 as their level of experience with computer programming. Python was the most common language reported (9/15 participants). Participants were paid $30 for an approximately 120-minute workshop.

6.5.2 Procedure

6.5.2.1 Pre-study

ConnectVR is a plugin for the Unity game engine. We asked study participants to install Unity 2020.3 on their Windows 10 laptop computers before arriving for the workshop. This enabled everyone to have the same version of the game engine setup for our plugin.

6.5.2.2 Onboarding

Before beginning, each participant was given a unique participant ID and asked to provide informed consent (protocol \#Anonymous). Participants were asked to fill out a pre-study questionnaire and were provided a link to download our Unity package containing the ConnectVR plugin. We guided the participants in installing the plugin, which took about 5 minutes. After successful installation, we spent 10 minutes walking participants through the necessary basics of importing assets and populating a scene with 3D objects. This was followed by a 30 minute tutorial session showing them how to use the ConnectVR system. The tutorial introduced participants to the visual programming interface and demonstrated how to create a simple interactive experience. Participants followed the tutorial and were encouraged to ask questions. The researcher ensured that each participant was able to reproduce the example experience before proceeding with the study task.

6.5.2.3 Study Task

After the 30 minute tutorial session, participants were given an open-ended creative task to complete in the next 60-minutes. We asked them to create an interactive short story using the ConnectVR interface. The story needed to have cause-effect relationships built using the visual interface. These relationships needed to define user actions and related consequences in the virtual environment. A low-poly 3D model library [287] that contained over 2000 prefab objects, was provided to enable participants to build their scenes and narratives without spending precious time and effort creating or finding 3D models. To scaffold creativity, we provided two basic scenes, a wild western town and a forest park. The scenes contained a Unity prefab object with the necessary ConnectVR components (e.g., the relational graph manager, an action visualizer, a user input listener) as well as a number of static 3D models (e.g., characters, animals, houses, vegetation). Participants needed to author an interactive narrative experience by creating their own relational graphs and converting their chosen static objects into interactable agents. The researcher observed the participants' authoring process, and answered questions. The questions were limited by us to topics regarding the system and the interface covered earlier in the tutorial. We did not answer questions related to graph authoring design unless they were specifically interface related.

6.5.2.4 Post-study

After the task session ended, the participants were asked to upload their projects to a cloud drive and fill out a post-study questionnaire about their experience learning and using ConnectVR. The questionnaire asked about the usability of ConnectVR and its capacity to support creativity as well as ease and efficiency in creating narrative experiences using the visual interface. All the questions were rated on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).

6.5.3 Results

All participants in the workshop, after a 30-minute tutorial session, were able to create their own interactive short stories, including those who had no prior experience in creating interactive narratives in 3D or in VR (P3, P5, P6, and P7).

6.5.3.1 Creative Task Outcomes

A summary of how participants created their short stories is presented in Table 3. Figure 48 shows example scenes from the participants' short stories. There were, in total, 120 actions defined by the participants, among which 24 were user actions and 96 were agent actions. In each story, the number of actions has a median value (*M*) of 8 and median absolute deviation (*MAD*) of 1. For user actions, the most popular user input methods to interact with the agents across all stories were avatar behaviors (13) such as *looking* and *body movement*, and verbal language with custom text-based messages (10). Avatar behaviors were used by eight participants and speech related interaction was used by three participants, with the other four participants using both. For agent actions, a total of 305 action commands were created. For each agent action, the number of commands has *M* = 3 with *MAD* = 1. Among all the agent action commands, the most popular commands used by the participants were movement related behaviors (21.6%) such as move around or move to a specific destination, and speak (18.3%) which enabled the virtual characters to talk to the user. *Generate* command was also commonly used but with a lower usage rate (7.4%).

In each story, the number of cause-effect chained relationships (those with unconnected head and tail) has *M* = 5 and *MAD* = 1. Among the total 93 chained relationships, the number of actions in each relationship has *M* = 3 and *MAD* = 1. Over 53% of the relationships have 3 or more than 3 actions and over 38% have 4 or more than 4 actions chained together. As the number of actions in a chained relationship grows, it becomes harder for the user to foresee the consequences brought on by their initial interaction. However, not knowing about all the consequences can lead to newer developments in the user's experience as they progress through the narrative. For example, lighting a campfire can attract animals in the immediate vicinity but a wanderer far away can also see the light and start walking towards the fire. The wanderer may or may not arrive at the campfire before the user leaves leading to one narrative thread. The user may encounter the wanderer later in the story leading to a different narrative thread. 13 participants incorporated relationships of at least 3 actions, and 4 participants explored longer chained relationships to make dramatic narrative outcomes. There were a total 147 interact-able agents created by the participants. The number of interact-able agents in each story has *M* = 8 and *MAD* = 3.

6.5.3.2 Questionnaire Responses

We divided the post-study questionnaires into three parts to separately evaluate: 1) usability, 2) creativity support, and 3) ease of building a relational graph with the visual interface.

Story Data Summary	
Stories	15
Actions	120
User actions	24
Agent actions	96
Action commands	305
Chained relationships	93
Agents	147

Table 3. Summary of workshop participants created story data.

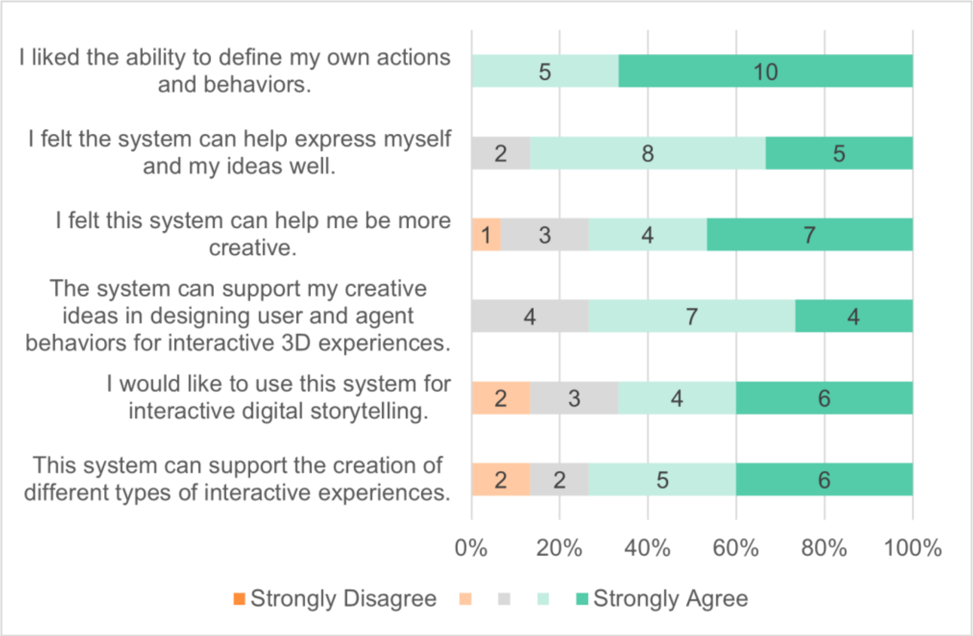


Figure 45. Results from questions related to creativity support of ConnectVR during workshop study.

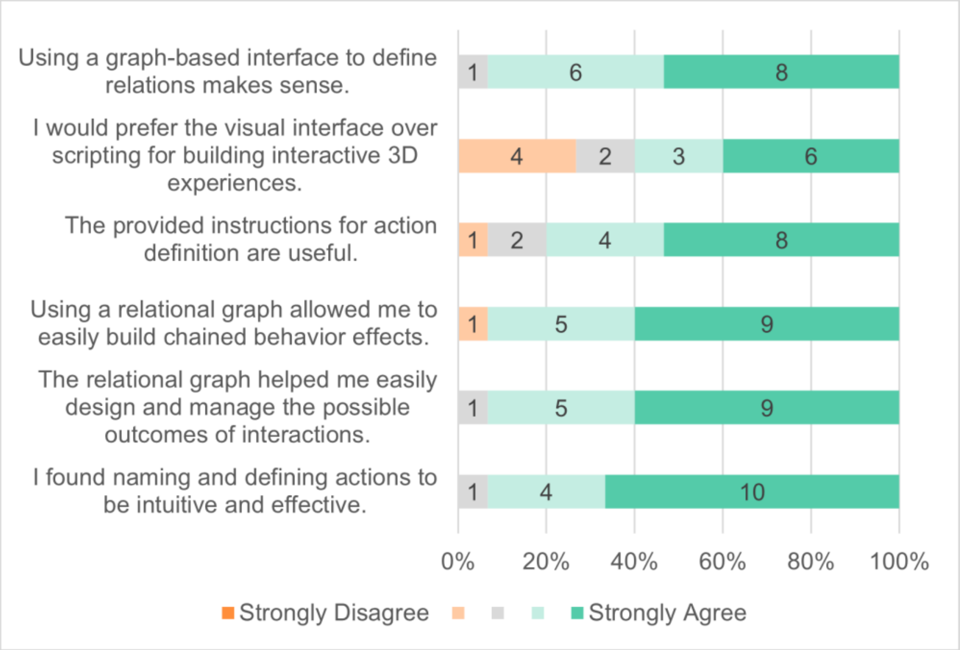


Figure 46. Results from questions related to easiness of building relations with visual interface by workshop participants.

Usability

Figure 47 shows results from questions related to usability of the ConnectVR system. 14 participants reported positive (average score of 4.4) indicating that the system and interface was highly usable and understandable. 12 participants agreed that most people could learn to use the system without any difficulty. 10 participants reported positive (average score of 4) that the system offers an easier way to create cause-effect based relationships that can be hard to do with other systems they have used, although one participant (P4) strongly disagreed with this. 12 participants were positive (average score of 4.1) about the process of creating behavior relationships being easy to understand. 13 participants agreed that the system allowed them to create experiences that they would have difficulty creating otherwise, with one strong disagreement by P11.

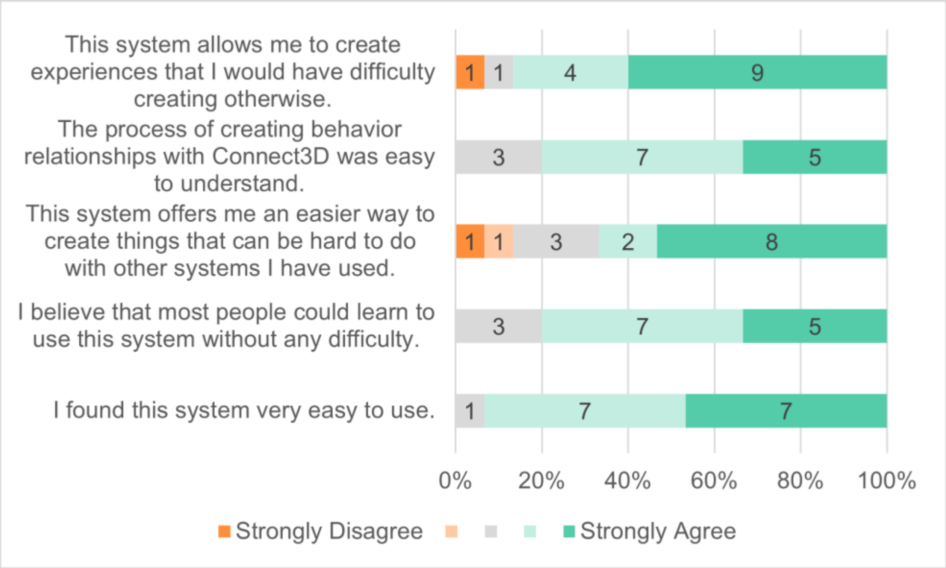


Figure 47. Results from questions related to usability of ConnectVR by workshop participants.

Creativity Support

Figure 45 shows results from questions related to creativity support of the ConnectVR system. All participants reported feeling positive (average score of 4.6) about being able to easily define their own actions and behaviors. 13 participants agreed that the system prototype can help them express their creative ideas well. 11 participants believed that the system can help them be more creative. There are also 11 participants showing agreement on the system's ability to support their creative ideas in designing user and agent behaviors for interactive 3D experiences. 10 participants indicated that they would like to use the system for interactive digital storytelling. 11 participants agreed that the system can support the creation of different types of interactive experiences.

Ease of Building a Relational Graph with Visual Interface

Figure 46 shows the results from questions related to ease of building a relational graph with the visual interface. 14 participants found naming and defining new actions to be intuitive

Figure 48. Example story scenes from the workshop creative task. Top left: (a) P1 created an art experience where hundreds of intelligent agents are aware of the user's presence and frequently attach to the user's avatar. Repulsive actions can be observed between agents of different colors, and they change colors upon collision with the large spheres. Top right: (b) P9 created a story in a forest where a user encounters a COVID-like virus seen in red. The virus object constantly duplicates itself and spreads upon being approached by wandering animal or human characters. Bottom left: (c) P13 created a walking simulator-like narrative experience using the wild western scene and placed eight different agents across the space. Each agent had its own behaviors and dialogues for the user to explore and listen to. Bottom right: (d) P11 made a fantasy land occupied by unusually large sized flowers and mushrooms where a user's movement triggered different behaviors on the objects such as dancing, singing, and changing scene lighting.

and effective. 14 participants agreed that the relational graph helped them easily design and manage the possible outcomes of interactions in the experience they were creating. 14 participants believed that using a relational graph allowed them to easily build chained cause-effect related behavior effects. 12 participants thought the provided commands for action definitions were useful and well placed in the interface. 9 participants indicated preference for the visual interface over scripting regarding building interactive 3D experiences. Among the 4 participants who did not prefer visual interface, two participants are computer science major with strong proficiency (self-reported score of 4 out of 5) in scripting language such C++ or Java, and another two participants from media arts background also had same level proficiency in programming with C# and JavaScript. 14 participants agreed that using a graph-based interface to define relations makes sense to them.

6.6 In-depth Evaluation

From the workshop, we understood that our system is easy to use and learn, and creators can possibly create various forms of interactive narratives relatively quickly. To further understand how our system can be applied to a real creative production environment, we conducted an in-depth study with two creators who used our system for one hour per day for a total period of 15 days. Based on this extensive usage, we designed our evaluation to, 1) see if our visual interface and workflow improve their creative process, 2) see if our tool enables the creators to produce new forms of creative experiences that they could not do before, 3) gain insights about how the tool may affect the way they think about creating interactive VR experiences.

6.6.1 Participants

We recruited two participants of creative backgrounds (1 female and 1 male) to use our system. Like our workshop, we looked for artists, storytellers and creative content producers with a particular interest or prior experience in interactive VR experience design. PA is a media artist and UI/UX designer with some prior experience in immersive and spatial experience design with Unity. PB is an undergraduate student with no prior experience in VR but has participated in making two 3D games by Unity in the past. Regarding their programming experiences, PA has limited technical knowledge of scripting while PB is more comfortable learning and writing codes in Unity. Both participants were paid for their approximately 20 hours spent during the 15-day period on a $20/hour basis, resulting in a total of $400 compensation for each person.

6.6.2 Procedure

6.6.2.1 Pre-study

We provided the participants with instructions to install Unity 2020.3 on their own Windows 10 computers before starting the study. We also provided technical assistance to the participants in setting up their Oculus Quest 2 VR headsets.

6.6.2.2 Onboarding

Before beginning, the two participants were given a unique participant ID and asked to provide informed consent. They were asked to fill out a pre-study questionnaire as well as a short pre-study reflection survey to report their existing experience with the process of designing and creating interactive VR experiences (if any) as well as their understanding of how the tools they have used in the past may have had any influence on their creative thinking and outcomes. The survey is composed of three questions and the participants were asked to provide an answer of 150 – 250 words to each of them. Then we guided the participants through the installation of the ConnectVR plugin and walked them through the necessary basics of using the ConnectVR system to design and develop an interactive VR experience. This step introduced the participants to the visual interface, the concept of an action-driven agent design, as well as some examples of creating multimodal user interactions based on voice and gestures.

6.6.2.3 Study Task

As the goal of the study was to see how well the system can help creators in real creative production, we invited the participants to design and deliver an interactive VR experience based on their own creative interest and practice after introducing them to the capabilities of the system. Then they were given 15 days to deliver this VR experience. The participants were given flexibility in prioritizing their creative tasks such as asset preparation, 3D modeling, interaction design, scene building, etc. They were asked to fill out a short survey each time they completed a creative session (typically once a day) regarding their specific creative goal of the session, the difficulty encountered if any, the overall feeling, and other comments that they would like to share. The participants were also asked to synchronize the project using Unity's cloud collaboration tool so that the researchers can examine their daily progress. The researchers collected those survey feedback and project updates, and then followed up with the participants every three days through a 15-minute zoom remote session to see if there were any technical issues that may be preventing the participants from moving forward, ensuring they could get the resources they need for thei VR experience development (e.g., 3D assets, hardware support). Similar to the workshop study, we provided the participants with an asset bundle of hundreds of 3D models to help them easily start prototyping and testing. It was up to the participants to determine whether they would like to use their own 3D assets or not.

6.6.2.4 Post-study

At the end of the 15-day period, the participants were asked to fill out another short reflection survey similar to the one provided at the pre-study step regarding their experience with the process of designing and creating interactive VR experiences, as well as how they think of the tool's influence on their creativity and creative goals. Then the researchers conducted a 20-minute semi-structured Zoom interview with each participant to understand their experience with the ConnectVR system. The questions were designed based on the evaluation guidelines for user interface systems [288] and HCI toolkit research [289], with a particular focus on expressive leverage, problems not previously solved, targeting population, functionality and general utility feedback. The interviews were screen-recorded after getting consent from the participants.

6.6.3 Results

Both of the participants were able to deliver their interactive VR experiences and successfully demonstrated their projects to the researchers at the end of the 15-day creation period.

6.6.3.1 Usage Survey

The usage survey was taken by the participants after each creation session. The duration of each session was determined by the participants based on their personal schedules. Although we encouraged the participants to try to have one session per day, their schedule was not distributed evenly every day. Therefore, some of the creation sessions were longer (> 2 hours) than the suggested minimum one-hour session. Both participants had a few longer creation sessions and we eventually received 11 usage reports for each participant. From these reports, we hope to glean a sense of their creative process, goals, and difficulties.

Creative Process

Both participants started by brief experimentation on the relational graph composition to test out simple interactions and behaviors. They built simple micro-scenes with a few virtual objects using the provided 3D assets to get familiar with the ConnectVR system. Then both reported in the usage survey that they started to design an original virtual scene and prepare corresponding 3D models that fit with their intended narrative. After briefly setting up an initial scene, PA started to design relations and interactions between different objects and characters. She took an iterative design approach going back and forth between interaction design and scene building. She indicated in her report that she was working on the scene design to make it consistent with user interactions and vice versa. PB, after the initial scene building, started to add virtual objects into the scene while also designing interactions for them. Among PB's 11 reports, there were 7 sessions in which he added behaviors and objects to the scene.

Creative Goal

In her 11 usage survey reports, PA reported twice that her creative goal was not met or only half met. The first time that her goal was not met was because she was struggling with designing the virtual scene and determining the overall conceptual theme of the project. The second time that she mentioned her goal was half met was because she was trying to design "relations and triggers with a timely order". She mentioned that it could be "a bit hard to

Figure 49. Example scenes from PA's interactive VR narrative. Left: the user can interact with food objects on a stove and the stove may explode upon touching. Right: the explosion of the stove leads to an avocado rolling on the floor and a virtual character begins to chase it.

visualize when different actions happen in a timely order.” Other than these two reports, PA reported positively about her creative goals being met without problems.

PB reported 10 times that his creative goal was met and mentioned only once that he could not reach his creative goal using the system on Day 2. The reason for this only failure was that he wanted to modify what different VR control buttons do and try to make the character fly without gravity, both of which were features managed by Unity’s VR input system. As this was the first time PB made an interactive VR experience, the researchers after receiving this feedback introduced him to Unity’s VR-related settings during the first follow-up meeting.

Difficulties

PA reported that the difficulties she faced were mostly about trying to design a sequence of actions in a timely order. Especially when there are multiple possible actions that can be triggered, it becomes hard to see if these actions are going to be activated as expected. She suggested having a visualized timeline so that the actions in play can help better debugging. The difficulties faced by PB were all Unity-related technical issues, such as post-processing, camera movement control, VR input system, etc. PB did not encounter ConnectVR-related issues.

6.6.3.2 Creative Outcome

PA designed an interactive VR narrative on the theme of a person's mental state. The work explores the state of being isolated from external social relationships. The narrative is staged in a surreal cave-like room with a number of furniture pieces such as a computer desk, sofa, stove, and lamps. There are also a number of virtual human characters that look identical to each other behaving differently in space. The audience can interact with these characters and they will move around in the room to trigger hidden features on the furniture pieces such as mysterious creature generation, object appearance change, sound effects, etc. Figure 49 shows the example scenes made by PA.

PB designed a mini VR game staged in an underwater environment. The player can move around in a cubic pool to collect various objects such as bottles and boxes, and then they can bring them back to a boat to get rewarded. While the player is navigating in the space, they may encounter ocean creatures such as fishes and moving grasses, and these creatures will notice the player and follow them. Figure 50 shows the example scenes made by PB.

6.6.3.3 Interview and Reflection Survey

During the post-study interviews, we asked participants to provide feedback on the strengths and weaknesses of the system and comparison with any tools that they might have used in the past. We also checked on their opinions about how the tools helped their creative process and goals, as well as their expectation for the system. The interviews were transcribed

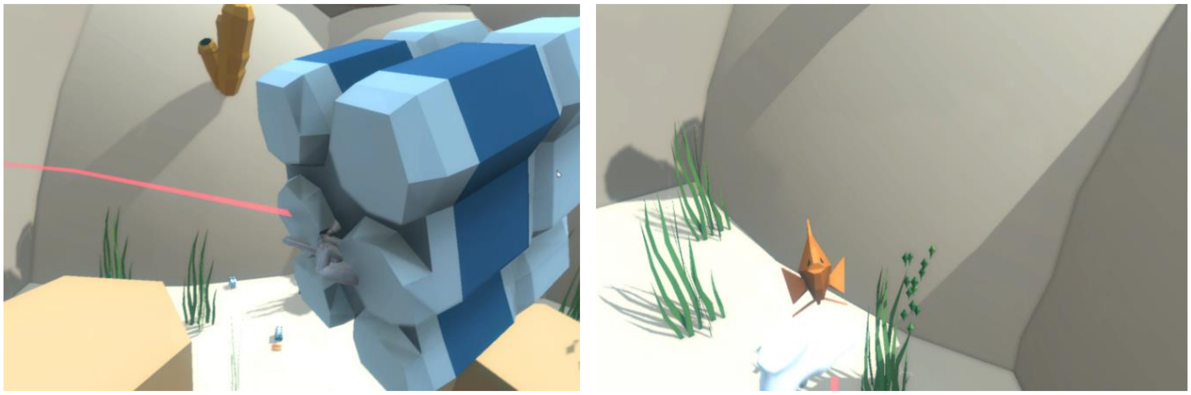


Figure 50. Example scenes from PB's interactive VR mini game. Left: the user can collect objects in an underwater environment and send them back to the boat for rewards. Right: the ocean creatures like fish and grass will follow the user when they are nearby.

by one researcher and the text transcripts were exported for qualitative analysis. Then we employed an inductive thematic analysis approach [201] on the interview texts in combination with the reflection survey write-ups, usage surveys as well as the actual creative outcomes. Based on these materials, we derived three themes: workflow fitness, time efficiency, and creative inspiration.

6.6.3.3.1 Theme 1. Workflow Fitness

Both participants found that the tool well matched their creative workflow. PA thought that our system fits well with both her creative goal and the process of designing expressive virtual agents of different behaviors in a VR environment. PA’s previous art practice focused on designing autonomous virtual creatures of animated movement in VR. In the study, PA included many animation clips for her virtual characters. The animations were triggered by different actions of other virtual objects as well as audience movement and body-related actions. In this way, she used our system to make her virtual agents more responsive and dynamic to the audience and the environment, which fit well with her creative goal. As a UI/UX visual designer, in her reflection write-up PA briefly compared ConnectVR with other visual design processes by saying: "*after using the tool, I feel the process of creating interactive VR experiences can be simple and straightforward like I do with other kinds of visual designs. It's very convenient to design actions by selecting predefined behaviors and design interactions by connecting each action*." PB, on the other hand, thinks that ConnectVR fits well with his typical process that the tool can be easily adopted into his regular way of creating an interactive experience, replacing all the scripting parts. He explicitly stated that, "*I was using it in a way as how I would usually go about my scene making process and just try to fit into my workflow instead of using it as an inspirational tool. It turns out that it works pretty well in doing these tasks.*"

6.6.3.3.2 Theme 2. Time Complexity

Both participants think this tool helped them save a significant amount of time to design interactions. PA thinks that the tool helped her overcome difficulties in motions and interactions which used to be "the most complex part" for her. But now this tool "largely reduces the complexity of creating actions" so that her VR world can be "more dynamic and interactive." PB thinks about time efficiency from the point of view that this tool replaces the scripting part in his workflow. He repeated several times that the tool in comparison to a typical scripting-based workflow provides a much easier way to create interactions and behaviors of objects. He said, "*when I was trying to create, I didn't really use any scripts or have to open up any scripts to change it, I just use the tool as given…I think it just replaces the scripting part.*" Similarly, when PB was discussing his own practice in the past, he mentioned how he would have done with the traditional way of creating interactive behaviors: "*I think overall it makes a lot of things faster because like I usually have to search things up if I want to make* *something. If I want to make something follow the player, I might want to search for Unity's API and have to go from there."*

6.6.3.3.3 Theme 3. Creative Inspiration

From the reflection survey, we observed that participants were quite aware of how different creative tools may influence their creative thinking. PA specifically mentioned that "*different creative tools increase my creative thinking in different aspects. This tool encourages me to think more about how different elements in the world can relate to and affect each other. It also helps me to extend my imagination to how VR audiences can participate and influence the virtual environment.*" This parallels PA's creation process during the study as we observe from her usage logs. PA took an iterative design process that goes back and forth between the agent action design and the scene building. In PA's view, the VR scene and the agent's actions need to match with each other for more effective storytelling. In one of her usage logs, she wrote: "*I have been thinking how the room scene is reflecting what's happening inside and transformed over time in a surreal way. I experimented with the claymesh tool to create hidden creatures and design their relation with the original room objects.*"

PB looks at the tool's influence in another way, as an effect brought by time efficiency. He especially emphasized the idea of flow in his creative process: "*When I create for long periods of time, I fall into a 'flow state' where I naturally get progress done without stops. Tools are meant to facilitate that process, instead of stopping the flow*." In PB's view, the tool must make him able to do fundamental actions faster so that he could "think of more ambitious ideas". Therefore, as PB believes that ConnectVR does significantly make a lot of things faster for him, he could then spend more time thinking about more interactions between different objects in an interactive VR experience design. He said: “*having a tool that does all this quickly allows me to do all of this in just a few seconds, and lets me test out more interactions because it isn't a time sink to do so*.”

6.7 Creative Production

As the goal of ConnectVR is essentially to support the creation of a new type of interactive VR narrative experience that is based on relations and interactions, it will be useful to also look at how our system can be directly used in actual creative production. Here I demonstrate two proof-of-concept VR artworks that are enabled by ConnectVR: *Look for Tardi* (2022) and *The Garden of Critters* (2023)

6.7.1 Look for Tardi (2022)

6.7.1.1 Synopsis

Look for Tardi is a 3D interactive fiction experience with a narrative structure weaved by moments of choice. The player steps onto a journey searching for the missing character named Tardi, traversing mysterious terrains and encountering nonsensical creatures. During the journey, rumors and stories about Tardi can be heard and the player will learn the hidden truth behind them. The choices and actions of the player will also affect what they find about Tardi and determine how the story ends. It is a story designed by the artist but activated by the player's own choices.

6.7.1.2 Features

Look for Tardi focuses on providing the audience with an experience of personalized discovery that is realized by unconscious interaction. Beginning with an experience similar to a walking simulator [290], the audience simply needs to spend a good deal of time moving around in the space and having conversations with virtual objects and characters, then an abstract cityscape will gradually appear in front of them. Figure 51 shows example views of the virtual scene and abstract cityscape in *Look for Tardi*. However, unlike a traditional walking simulator, the city landscape is not a static terrain that is pre-defined by the artist. Instead, based on the order of where the audience goes first, different city components will be activated and rendered. The audience is unconsciously determining how the city may expand or grow into different states. During this process of "unconscious unfolding", the audience therefore will find different and exclusive hints and messages about Tardi by conversing with characters and objects unique to the pattern they unconsciously chose. A highly personalized narrative is therefore created and activated by the audience, and their participation in the narrative space also contributes to their imagination of Tardi.

Figure 51. Selected screenshots from *Look for Tardi* (2022). Left: floating text messages in VR scenes that the audience may encounter upon interacting with certain virtual objects made of abstract lines and curves. Right: the virtual environment starts to expand and grow larger with more abstract buildings appearing after the audience spent some time in the space exploring different areas in the environment. The appearance of this virtual city is dependent on the audience's choice and movement that every time the city may grow into a different shape.

With the support of ConnectVR system, this idea of unfolding cityscape becomes possible. The appearance of specific city areas can be chained together as actions only triggerable by specific causal actions. These causal actions include events such as the audience’s movement, a virtual character’s speech, a hint about Tardi being picked by the user, etc. Every action in the story can be designed as a meaningful cause for the expansion of the virtual city, resulting in a large space of possibilities and combinations. ConnectVR also made it simple and straightforward to design virtual characters’ voice play, telling the story about Tardi to the audience in a more expressive and natural way.

These features in *Look for Tardi* constitute a two-layer narrative structure – the first layer is based upon the story designed by the artist of searching and unfolding where Tardi has been, and the second layer is based upon the audience’s own journey of searching by their choices of visiting and exploring. Especially for the second layer, it is a narrative unique to each audience that their participation leads to their own imagination. Every audience will have the chance to find their own idea about Tardi since they step on different paths of searching. The narrative, therefore, depends largely on the audience instead of the artist.

6.7.2 The Garden of Critters (2023)

6.7.2.1 Synopsis

The Garden of Critters speculates about a futuristic scenario where tech companies utilize AI algorithms to generate and propose new types of life forms. Meanwhile, consumers from the social media platform collectively decide which kind of life form archetypes can be put into production and be piloted in an experimental site – a virtual ecological system to incubate these creatures while being watched by the public. Life-form archetypes that win higher “likes” are more likely to be created and eventually permitted into human society as a new critter product.

While the selection and incubation process is automated by AI algorithms, there are still human operators behind the tech companies for symbolic functions. The daily life of *X*, who serves as a creature designer at MegaFuture, is full of shifting duties. Her routine work is to initiate new life-form strategies, align stakeholders of various interests, tweak generated creatures, and push them into production. While being a small part of the system, *X* is eternally flooded with numerous data, conversations, and documents.

6.7.2.2 Features

The main interactive VR experience of *The Garden of Critters* is staged within a virtual creature incubator zone that is surrounded by concrete materials and glasses (see Figure 52). The incubator is populated by AI-generated critters of various forms that have their own autonomous behaviors. They may move around the space or be attracted to specific objects or follow other critters to formulate some emergent behavioral patterns. The audience can approach these critters to interact with them by looking at their faces, touching, or grabbing them, and these critters will have unique responses to such interactions, displaying a level of intelligence to the audience. Every a while, a pair of huge virtual hands will appear in the sky, opening up a virtual gate where new critters will be dropped into the incubator zone. In this way, the space will be gradually populated by various critters and the audience will have new opportunities to get to know and interact with more types of critters over time.

ConnectVR was used mainly to design various interactive behaviors of these virtual critters. Composed of a large relational graph, many of these behaviors can be triggered by

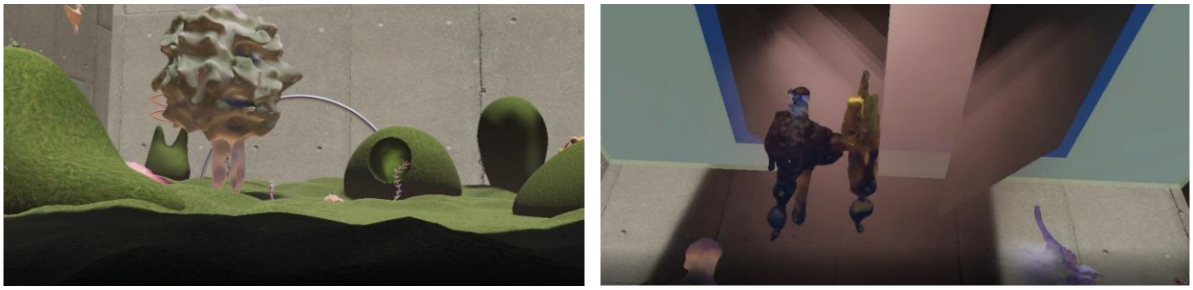


Figure 52. Selected scenes from The Garden of Critters. Left: the entrance of the creature incubator zone. The space is filled by organic artificial plants, animated critters, and flying micro-organism which the audience can interact with by touching, pickup, or simply standing in front of them. These critters will respond to the audience's specific behavior and display animations as a way to non-verbally communication with the audience. Right: a window in the ceiling sometimes opens up and drops new critters into the incubator zone. Two large hands will appear at the same time to indicate that new members are joining the space.

user gesture input. Different animation clips of the critters can also smoothly transit between each other, together formulating a rich narrative experience that is activated by the audience. Autonomous behaviors were also designed as individual actions so that the critters can exhibit a wide range of behaviors, turning the virtual space into a lively ecosystem of diverse species. On the utility side, ConnectVR was also used to compose the inherent mechanisms of the virtual environment. Special events such as the appearance of virtual hands, virtual gate opening, and new critter spawning, are all handled by a set of actions made of utility commands. They are chained together as sequences of actions to support the experience mechanisms behind so that these events can unfold in the desired order without conflicting or competing with each other. In this way, the virtual world is no longer a static preset stage but a dynamic changing environment of unexpected occurrences of different new events.

6.8 Discussion

Our results indicate that ConnectVR is generally easy to learn and use and provides a simple way to create VR interactive narratives based on complex cause-effect relationships.

6.8.1 Interaction-driven Storytelling

From the workshop study, we can see that participants were very positive about the system's capability to help the creation of interactive narrative experiences. Particularly, we noticed the frequent use of actions related to user avatar movement or speech, leading to a style of narrative experience composed largely of the user exploring the virtual environment and engaging in conversations with virtual characters. Based on the popularity of these two types of user interaction methods, we speculate that participants preferred to use natural and familiar ways of interaction to trigger the narrative events with virtual characters. Virtual agents (e.g., humans, animals, trees) that appeared in 12 stories were designed similarly to gauge a user's movement or identify attention (when the user looks at them) to automatically start a conversation with the user or trigger other story elements. For example, in P15's story, a churchgoer can see and greet the user from afar by saying “Hey there, Space Man” (the default user avatar we provided was a spaceman figure) when the user seems to be heading towards the church entrance. We see using natural user behavior as a way of starting an interaction an interesting effect favored by our participants. This observation parallels the creative outcomes we get from the in-depth study. Both PA and PB’s creative projects adopted similar strategies to let the user’s natural interaction trigger agent actions, such as pickup, touch, and approach. Natural user interaction therefore can be considered a highly desired feature for creators to design and build interactive narratives.

On our usability-related questionnaire, we have two strong disagreements by P4 and P11. We speculate that the reason why P4 disagreed with our system being easier than other systems they have used is because of their background as a film student. P4 reported in their pre-study questionnaire that they have experience designing and creating film and video game-related

3D assets. As our current system is aimed at creating 3D interactive fiction not 3D assets, it likely does not match their expectations or creative requirements for making film-like experiences. We speculate that the reason for P11's disagreement on our system's ability to ease the difficulty in creating narrative experiences comes from their proficiency in computer programming (C++, C\#, Java and JavaScript) with a self-reported score of 4 out of 5 on a Likert scale (1 = not at all, 5 = A great deal), as well as high familiarity with programmatically creating interactive 3D experiences with Unity (a self-reported score of 4 out of 5).

6.8.2 Diversity in Creativity

Our system's ability to support different types of interactive experiences was seen in both the questionnaire results as well as the created stories. The experiences created by participants of the workshop showcase diverse narrative themes such as a treasure hunt (P6), a zombie breakout (P12), the lives of churchgoers (P15), and workers in protest (P3). The narratives are presented in different formats such as an art experience (P11, P1), a generative system (P9) and a mini-game (P14). For example, P11 created a fantasy land occupied by unusually large-sized flowers and mushrooms where a user's movement triggered different behaviors on these objects such as dancing, singing, and changing scene lighting (Figure 48). P14 created a game-like story where a T-Rex chases a group of people and the user's goal, hinted at by a virtual character, is to left-click the mouse to shoot pineapples at the T-Rex to stop it in its path. P9 designed a generative mechanism using the provided *Generate* command to procedurally spawn interactable agents upon each action trigger. In P9's story world, a user encountered a COVID-like virus in the forest. This virus object duplicated itself and spread upon being approached by wandering animal or human characters. This mechanism, simulating a possible real-world scenario, made it hard to predict how far and how much the virus would spread over the story world. These examples of interactive relationships were unexpected and we believe support the idea that our system can allow for a large amount of flexibility and creativity.

Furthermore, from our in-depth evaluation, we also see how differently the two creators used our system during their creative practice. Both creative projects were going along with the creators' own practice and interest that they could well integrate our system into their typical creative workflow. PA used the system to extend her practice of designing interactive creatures, with a focus on associating user interactions with character animations. PB used the system to design game mechanisms and replace the need for scripting. The two ways how PA and PB used ConnectVR demonstrated the advantage of our system in helping deliver a code-free authoring process.

6.8.3 Visualizing Outcomes

From the workshop evaluation, participants responded positively to the creation of chained behavior effects though most of the chained relationships they created were not very long ($M = 3$) actions in each chained relationship). This might be because of the limited time available during the workshop to think and build. It was rare to see participants design "butterfly effects." While the system enables easy implementation of the butterfly effect, thinking of plausible effects that may grow over time may not necessarily be easy or fast. The longest chained relationship we observed was in P10's story depicting a gun fight between two cowboys using seven chained actions. P10 designed a scenario where the user is confronted by a gun fight between two cowboys and is given two options, either to stand by the one who is the husband of a lady or stand by his rival. Choosing the rival triggers a sequence of actions (the husband dies, the lady screams, horses escape and run into wooden crates that explode) and consequences that end with the burning down of the village. Our initial intuition is that the design of a long sequence of cause-effect relationships may require careful planning of the story and reasoning of interactions between different agent behaviors, which can take more time and effort than was available during the study.

During our in-depth study, we noticed that PA was trying to design longer sequence of cause-effect relationships but encountered some difficulties in visually previewing the possible outcomes. She mentioned in one of her usage reports that “it is a bit hard to visualize when different actions [will] happen in a timely order.” After checking PA’s project source files, we noticed that the longest chained action sequence has 8 actions. Combining her comments on visualization and her actual implementation, it is reasonable to say that with careful planning of the story and interactions between agents, it is possible to design some “butterfly effect”, however, it same as how a butterfly effect can turn out to be unpredictable, designing such a complex phenomenon requires extra visual aid to help the creators not just be able to create and implement it, but also preview the possible outcomes. As the spatial and temporal factors can vary in different scenarios upon user interventions, the creators may want to have some easy way to see and check what an agent do if it is somewhere doing something and another agent is doing something else and so on. This will require some extra work on the visualization for the procedural outcomes of relational actions, and good interface support that may encourage the creators to design more complex butterfly effects in a virtual environment.

6.8.4 Artistic Novelty

Even though the creative outcomes from the workshop were limited by the one-hour limit of the creative process, we are already able to observe some artistic novelty enabled by our system. P9’s virus-spreading effect particularly stands out as it is quite unusual to see this type of strong social dynamism in an interactive experience. In P9’s virtual environment, once infected by the virus, an agent or the audience will become infectious and may spread the virus effect to other nearby virtual agents. It is a highly unpredictable process inspired by real-life scenarios but enabled by very simple action design by a spreading relation (Figure 43). This mechanism builds up a subtle and somehow antagonistic relationship among all the agents in a virtual environment, challenging the way how the audience may respond to the dynamic movement made by various virtual agents and amplifying their “social responsibility” in a virtual environment. P1’s interactive flocking system is also a highly dynamic procedural art piece where hundreds of abstract geometries are moving and attracting each other according to the audience’s position and gesture. Unlike a traditional flocking system that needs to be scripted with specific rules such as alignment, separation and coherence [291], the effect of flocking in P1’s experience is simulated by utilizing the “*Follow*” and “*Go To*” commands provided by our tool while linking different types of actions together to make these agents frequently switch action targets and find the audience’s position change. The result of this flocking design takes more consideration about the audience into the effect than an original flocking simulation, which improves the audience’s sense of engagement and connection with the dynamic schools of virtual agents.

Artistic novelty can be further observed in our in-depth study. PA’s art project also displays some strong artistic novelty leveraging upon the sense of participation brought by the capabilities of the audience to intervene and disrupt the virtual environment. PA’s narrative experience is staged on a theme of “isolation”, and the artistic goal of the work is to explore the idea of loneliness and self-indulgence caused by external factors such as social exploitation and the global pandemic. With this goal in mind, PA decided to recreate a similar living state that is isolated from the external world in a surreal manner. The protagonist, a human character, was represented as several different avatars displaying nonsensical and repetitive behaviors such as talking to the window, meditating, sleeping, or chasing random objects. Through these unusual behaviors, PA tries to instigate the audience’s imagination and reflection about what causes a living or mental state like this, bringing up a broader theme about the emotional and social needs of human beings. On the other hand, because the work of art is situated in a VR environment, the audience is also transported into the same room where the protagonist lives. Walking, investigating, and interacting with the same furniture pieces as these virtual characters do, the audience in this way also becomes one of the avatars that represent the protagonist. This leads to a projection between the audience and the protagonist that not only the audience can embody the avatar of the protagonist living a fictional life, but also the protagonist can be the audience in real life. In some sense, PA created a virtual reality that highly references the real world, and by the design of these direct interactions performed by the audience, this sense of reference gets amplified into a much stronger association between the virtual and the real, making the entire VR narrative a lot more plausible.

6.9 Limitations and Future Work

Our current system provides a library of a limited number of commands for action definitions, which can certainly be expanded to accommodate many more user and agent behaviors. Although our participants, including the participants from the in-depth study, think that the currently available commands can well cover most of the storytelling needs for their creative practice, the ability to customize or create new commands will help raise the ceiling of the expressiveness of our tool even further. PB suggested that it will be useful to include more detailed interaction state specifications such as action begin, action-in-progress, and action end so that more accurate control over the timing of an event can be designed. In addition to that, both PA and PB noted that commands such as *Follow* and *Wait* are “handy” to use as they think that it will be hard for them to figure out how to implement if they have to do all the scripting behind. Therefore, we see these commands which are common to our daily life but hard to implement as potential design opportunities for non-technical creators. Another limit as we have discussed is the visualization of possible outcomes after designing a long sequence of actions as mentioned by PA. The procedural nature of designing a butterfly effect or a chained reaction makes it particularly difficult to foresee how subsequent actions that are not directly triggered by a user interaction or an initial action due to the uncertainty in these actions’ temporal and spatial conditions. A faster way to iterate or easily set up these temporal and spatial factors may be helpful to let the creators preview what may be upcoming from an initial behavior.

While ConnectVR focuses on creating cause-effect chains, there are other forms of interactive narrative creation that full game engines might allow for expert programmers that is beyond the scope of the current paper. Instead, we explored the possibility of making a VR experience easier for non-technical users and showed that ConnectVR is capable of allowing artists and storytellers to build relatively complex narratives in a variety of formats from art experiences to games. In our future work, we will first address adding the ability to create custom commands for user-defined actions to make the system more flexible. A comparative study between our interface and other visual interfaces for VR interactive experience creation such as Unreal Blueprints or Unity Bolt may be needed to further investigate the unique perspective that our cause-effect relational graph provides. Another aspect for future work is the inclusion of concept development assistance with AI planning algorithms for complex scenario designs, which may be useful for expert writers and storytellers.

Our main focus is to explore the possibility of the easy creation of interactive VR narrative experiences with complex cause-effect relationships by non-technical creators. We plan to continue our exploration at different complexity scales (e.g., agents capable of a large number of actions, butterfly effects on a large group of objects) in the future. Our current system hasn't yet been able to provide enough assistance in the conceptual development of a narrative such as brainstorming for complex scenarios, which would be useful for expert writers and storytellers.

6.10 Conclusion

In this chapter, we presented ConnectVR, a visual interface and workflow to support the code-free building of cause-effect relationship chains for creating VR narrative experiences. To enable an easy way to connect a user's actions with resulting virtual agent behaviors, we introduced the idea of using a relational graph implemented with block-style programming to simplify authoring. We presented details of our system design and features that support the 3D narrative authoring process, targeted at non-technical creators. A workshop study conducted with 15 participants evaluated the usability, creativity support, and ease of building the relational graph using the visual interface. We further tested our system with two creators to extensively use our system for their creative projects. Our results show that participants were able to build their own narrative experiences using ConnectVR and our system is easy and intuitive to use and helpful for code-free creative storytelling. The use of a relational graph to define actions and cause-effect relationships was quite successful with evidence showing that the ConnectVR system provided a usable and easy-to-use interface for authoring expressive interactive narratives.

7. DISCUSSION

As mentioned in Chapter 1.3, my research is divided into three aspects: concept, practice, and creativity support. Starting from the concept of relational reality (Chapters 2 & 3), I designed and created art experiments (Chapter 4) as proofs of concept. Then, to generalize the findings from the experiments, I developed and evaluated a set of authoring tools to support the creation of relational reality using different strategies (Chapters 5 & 6). What’s next is to further have these three aspects inform each other so that we can reflect and combine the insights learned from each aspect. In this chapter, I revisit these aspects based on what we learned from all the presented projects, with the hope that we can derive and develop new knowledge from this reflection process.

7.1 Authoring Relations

To create a virtual reality, it will be helpful if one knows how reality is composed. To design relationships and interactions for human participants, it will be useful to know how social dynamism is formulated. However, from the fundamental physics of matters and materials to the high-level societal formation, there is not a clearly visible connection between the microscopic and the macroscopic phenomena for us to see and trace. My authoring tools EntangleVR and ConnectVR are designed with the goal of simulating the complexity of reality. Both take a different approach in letting the creators touch upon this complexity. EntangleVR departs from a more technical point of view focusing on how our reality may be composed of low-level particle interactions at the quantum level, while ConnectVR takes an interaction design point of view with an emphasis on how high-level agent interactions may lead to a diverse space of possibilities that no one can easily predict. Both authoring tools support different creative processes and enable different types of outcomes. Of the two, ConnectVR is relatively more advanced as it offers more flexibility for the creators to define their own agent actions using a wide range of preset commands. Here I present a brief comparison between the two authoring systems to evaluate their opportunities and tradeoffs between them.

7.2.1 Relational Play

The first thing we consider for this comparison is the way how they allow creators to design plausible relational effects. EntangleVR provides two main interaction design methods: 1) probability amplitude, and 2) entanglement. Probability amplitude is used to describe the behavior of a quantum system, which the creators can map to determine the observation outcome of a super object. Driven by the state of a qubit, it lets the creator design “controllable” randomness to add variety and unexpectedness to user interactions in a VR environment. Entanglement is used to introduce a correlation between two or more virtual objects. Surpassing the limit of spatial distance, entangled super objects will display correlated behaviors upon user interaction. This effect provides the audience with a sense of connectivity between everything as well as the capacity to make their own choices in a virtual environment. As entanglement can also be used in combination with probability amplitude to design a probabilistic correlation between objects, a mixture of the two techniques can lead to a virtual narrative scenario that appears plausible.

Departing from some of the ideas in EntangleVR, ConnectVR takes a metaphorical strategy in building entangled relationships between virtual objects. With a goal to deliver a code-free authoring experience, it simplifies the computational steps to enable correlated behaviors by introducing an arbitrary causal link between action events modulated by spatial and temporal factors, so that there can be more variations about how an audience or a virtual agent may affect or be affected by another. Although ConnectVR does not focus much on probability-driven interactions, the flexibility offered by customizable causal links can produce a wide range of relational play that is complex and able to give the audience a sense of plausibility.

If we compare the two sets of strategies, we may find that, as a system designed earlier, EntangleVR does not quite provide temporal control for its interaction design. Although the idea of entanglement was well received by the study participants, the lack of temporal control limited its applicability in providing a more general creative authoring experience. For interactive storytelling of a larger scope than what was tested, we would need to include an extra time-related mechanism to work with the idea of entanglement. ConnectVR does not have this issue as every interaction is constructed through a causal link, which one can manipulate by altering its spatial and temporal parameters. It is even possible to approximate the idea of entanglement by creating an immediacy between two actions, though the creation concept behind this approximation will be quite different from the actual entanglement. Given this flexibility in relational play, ConnectVR does not have many limits on the user’s creativity and can be considered a more general-purpose tool than EntangleVR.

7.2.2 Visual Interface

While both authoring systems provide a visual programming interface for non-technical creators to compose interactive virtual environments quickly and easily, the fundamental rationale behind each interface is different. EntangleVR adopts the idea of quantum computing to enable qubit manipulation and entanglement composition. Visual programming is chosen to ease the learning curve of relatively difficult concepts such as qubit, probability amplitude, and entanglement. By introducing reactive and real-time visuals (e.g., Bloch sphere) that represent the quantum states one is playing with for virtual objects, EntangleVR's interface aims to teach its users how to integrate the idea of entanglement into their creative composition. Although EntangleVR has a limited number of ways to support user input, it is easy for creators to test immediate interaction output by using the real-time preview window, which can potentially accelerate the creation process.

ConnectVR's interface is based on the idea of a code-free authoring workflow. Taking inspiration from block-based visual programming, it aims to further reduce the need for computational thinking by providing only one type of building block – action unit – to represent all the actions that may take place in a virtual environment. In this way, the creators only need to think of what actions they would like to design, and stack preset micro-action commands into these action units. The process of drawing lines between these units is also designed as a symbolic indication of causal relations between actions instead of a sign of data flow or operation.

During the evaluation, both authoring tools achieved high scores on visual interface-related questions. The feedback for EntangleVR's interface mostly focused on its learnability in providing the user with a good understanding of quantum concepts as well as its reactiveness in allowing a fast preview of virtual scene editing. ConnectVR's feedback indicates that the visual interface is considered a valid replacement for scripting to support a code-free workflow. If we compare both interfaces with existing tools on the market, we may see that although EntangleVR does provide a simplified way of creating interactive VR scenes, it still requires the user to engage computational thinking. The integration of quantum computing concepts contributes to a new way of designing interactive relations for virtual objects, but it does not go beyond the domain of programming. Its visual programming interface has typical elements such as data objects, operators, and functions, and the user needs to think like a programmer about the experience they want to create instead of thinking at a higher-level of phenomenal design. Conversely, ConnectVR goes a bit further than EntangleVR by further reducing its requirement for prior knowledge of programming concepts. Not only does it not require any scripting, it also does not require creators to think of the low-level technical details. ConnectVR's visual graph displays minimum programming traits and avoids explicit low-level algorithmic thinking during the creation process. Because of this, ConnectVR could help the creators be more focused on the high-level design of relations and interactions, encouraging more human-like creative thinking.

7.2 Rethink Relational Aesthetics

When Nicolas Bourriaud first proposed his idea that relations can and should be the subject of art, the creative community might have imagined a future that a work of art can someday be fulfilled by digitally simulated virtual relations as an inevitable result of the evolving digital society. Indeed, new media artists in the past few decades have attempted to deliver interactive experiences that can lead to new relations between the audience and the artwork by methods such as algorithmic art, interactive systems, and multimedia installations. These works were fresh and new, and they pushed the boundary of art into new territories. However, these works of art were rarely seen as something that can provide the equivalent type of relational experience as those we may encounter in real life. In today's discourse of relational art, the interactive artworks made by new media artists are still largely missing. The translation of virtual digital interaction into a relational experience seems particularly difficult as there is not just a technical but also a conceptual barrier that we need to surpass.

The technical barrier, as I have discussed in the previous chapters, resides in the way we may leverage the power of immersive technologies as well as the design of interactions to lead to relations. My conceptual strategies for constructing a relation reality suggests a process-oriented way inspired by Bruno Latour's actor-network theory to make it easy to see and even implement various types of connections and interactions between different human and non-human agents. This idea has been demonstrated in my art experiments as well as my authoring system ConnectVR. However, after creating these works and empirically evaluating my system, I also noticed that enabling interactivity in a work of art does not simply mean that the audience will always perceive the presence of relations. In some sense, creating relational art is still not the same as creating an interactive work of art. There exists a gap between the two types of experiences. If we recall the idea of the technical-cognitive split from Chapter 3, interactivity should be on the cognitive side that exists as a phenomenon of the relational reality, while its implementation and code need to be on the technical side. For the perception of relation, we may need an extra level in the split, in which we place interactions on the technical side and relational effects on the cognitive side. The reason for this extra split is that relations may not immediately emerge as a perceptible outcome of an interactive experience.

Particularly it requires a sense of plausibility that is to be established during the audience's various interactions within a virtual environment. This is similar to how Latour's theory frames, the more actions an actant performs, the more real it becomes. Relations are the history of actions and their perception relies on the realness of actants. As the designer and creator of a relational reality, we may be able to immediately think of the presence of some relation when an action has been performed because we are tuned to think in this way, but for the audience, it requires some iterations or repetitions of an action performance so that they can see and infer the presence of a relation behind it. The actant needs to be stabilized in the audience's mind to a certain level before a relation can be clearly perceived. Therefore, in a dynamic virtual reality experience, it is often observed that the audience may see many interactions between different things, but they may only recognize a few relationships in between. The creator's conception of relation yields to the perception of it by the audience.

The conceptual barrier perhaps is a more serious issue as it resides in the larger context of relational aesthetics itself. There is a hidden expectation for physical interaction in the formation of a relational aesthetic experience. This expectation can be observed in Bourriaud's text that the new media practice of art was "all but absent from his analysis" [292], and the examples referenced by Bourriaud were mostly participatory forms of physical interactions that focused on relations between humans and communal physical space. That is not to say that Bourriaud holds a view against digital interactions, or that he has a preference for certain types of artistic forms. Indeed, it is a more complex situation regarding the creative foundation of new media art as art historian Edward Shanken points out:

> "The operational logic of the mainstream contemporary art – its job, so to speak – demands that it continually absorb and be energized by artistic innovation, while maintaining and expanding its own firmly entrenched structures of power in museums, fairs and biennials, art stars, collectors, galleries, auction houses, journals, canonical

> literature, and university departments. As such, their power, authority, financial investment, and influence are imperiled by perceived interlopers, such as new media art (NMA), which lie outside their expertise and which, in form and content, challenge many of MCA's foundations, including the structure of its commercial market. The complex and uneasy relationship between NMA and MCA is hardly new. But the growing international stature of NMA and the seemingly irrepressible momentum it has gathered, make MCA's ongoing denial of it increasingly untenable…More research on unplugged examples of MCA might offer significant insights into the implications of science and technology and into the relationship between human and non---human agents. Such work might also offer useful perspectives on how NMA can be more successfully rendered and presented in exhibition contexts. One of the frequently noted shortcomings of NMA is that it does not satisfy the formal aesthetic criteria of MCA. In part this failure can be explained, if not excused, on the basis of the nature of the media and the theoretical commitments of the artists working with them." [292]

According to Shanken, it is more about the inertia in MCA that slows down the translation and introduction of digital virtual interaction into the relational aesthetics framework. Much like how society may not (be willing to) endure a radical structural change at the fundamental level, it may be true that contemporary art appears a lot more serious on the conceptual level or social commitment of a work of art as required by the institutional players behind it, and a relational art practice proposed by Bourriaud also follows this tradition i.e., one needs to answer why there are relations involved in a work of art and how important they are. In this sense, simply designing interactions from a technological point of view may not be sufficient to fulfill this requirement of being relational art. From my own experience, I also see interaction design as trivial if there is no strong reason for the experience to be interactive. An interactive experience of art may hardly be differentiated from a mini-game when the conceptual motivation of interactivity is not well defined. Similarly, one has to admit that interaction does not necessarily contribute to a good storytelling experience. The mainstream storytelling projects are still largely in non-interactive formats such as film and drama. Only when interactivity can establish a meaningful relationship between the narrative elements and the audience, we see the emergence of a successful relational art narrative. Under this premise, creating a meaningful relationship is part of the goal of creative storytelling, instead of just a method toward a goal.

By reflecting upon the relational aesthetics with reference to the creative projects in this thesis, we can see that enabling the design of relational experience from a technological point of view is important but it does not waive the creative responsibility of an artist in justifying the why of interactive storytelling. An artistic and creative mindset is still highly necessary during production. If we look at ConnectVR's evaluation outcomes (Chapters 6.5 & 6.6), the creative projects from both the workshop and the in-depth study could not be produced without the unique interests and backgrounds of the participants. The wide spectrum of the participants' creativity led to a wide variety of narrative experiences, even though they were provided the same toolkit and asset bundles. At the same time, we cannot ignore the value brought by the authoring tool while giving credit to individual creativity. Unlike a commercial product in that the value resides in its finalized form, a relational narrative experience focuses on the process of interaction and engagement, each of which contains an inherent aesthetic value. Therefore, as what we have observed from the interviews and reports of the participants (Chapter 6.6.3.3) that the usage of a tool can influence the design choice of an artist as well as their creative thinking, an authoring tool like ConnectVR that enables new types of interaction design has the potential to contribute directly to the value creation process. In the context of relational art, this contribution should be considered significant as all the possible relations one may experience are processed, influenced, and determined by it. The role of a tool-maker in this sense is also an indirect participant in a relational experience, leaving an enormous conceptual and design space for us to think about the future of relational aesthetics.

8. CONCLUSION

Duchamp once said, “art is a game between all people of all periods”. With the increasing usage of digital simulation and virtual reality, the evolution of art is a process of gamification – we are now all becoming the players of a larger virtual territory within a new ecosystem of various relations. My overriding goal of this thesis is to propose a new way of thinking about the design of a relational immersive experience. Motivated by Nicolas Bourriaud’s relational aesthetics and Bruno Latour’s actor-network theory, I have proposed a set of design strategies for a relational reality that focuses on adopting process-oriented thinking in connecting various human and non-human participants together for the design of a complex dynamism that elicits a strong sense of plausibility. The projects presented in Chapters 4 - 6 demonstrate how these ideas can be applied in the actual creative application as well as the design of new authoring toolkits to raise the ceiling and lower the floor of creative expression for non-technical creators. In each project, I propose novel techniques and concepts for creating a relational experience, and I show how they can be applied to deliver a new type of immersive narrative with a strong sense of plausibility. I hope my concepts, design strategies, techniques, and example applications can provide broader inspiration to the creative community to create new relational virtual experiences.

8.1 Summary of Relational Creation

In a relational reality, the creator's role is to design and enable actions that lead to relations between participants and virtual agents. There is no limit to how we may conceive of an action, but due to the lack of technical or authoring tool support, we often have limited choices to enable certain types of actions. Especially in a virtual environment, as there are no physical constraints about how things are connected or how they interact with each other, there is a huge design space for actions and relations. New techniques in both hardware and software can be introduced to enable new relations.

For human participants, the types of relations that they can build with others are tightly connected to the interaction modalities as well as the design of virtual agents. My experiment with soft robotics in Biometric Visceral Interface (Chapter 4) allowed the participants to remotely reach out to each other by haptic sensation across the physical boundary. In addition to the common visual and auditory communication, an extra haptic interaction between the two participants made their perception and experience of each other more real. At the same time, the usage of soft materials on the body provided an illusion of real human touch, which created an intimate relationship between the two participants. Eccentric Nature explored the possibility of simulating a virtual ecology composed of human participants and virtual intelligent agents. Through the design of a series of dynamic interactions and chained behaviors performed by various virtual agents, this work provided human participants with opportunities to establish equal but diverse relationships with non-human entities.

For non-human participants, it is often up to the authoring tool to let the creator compose complex relational narratives. SceneAR provided simple and easy ways to compose scene-based micro-narratives in AR. It allowed the users to create, view, share and remix all in one place on a smartphone where they could see each other’s stories and compose new narrative sequences together. Our user study particularly showed that people felt a sense of connection and collaboration even though they did not know each other. EntangleVR explored the possibility of integrating quantum entanglement for storytelling and interactive scene creation for virtual reality. It demonstrated that a new computational paradigm can be successfully used to design interactions in a virtual environment, therefore leading to new relations between human participants and virtual objects.

Following all the experiments and technical discoveries of relation creation, ConnectVR was designed to provide authoring support for both multimodal interaction design and complex action-based narrative at the same time. The authoring interface leveraged the concept of action differentiation to help the creators follow a process-driven creation method so that they could directly design virtual phenomena for human participants and smart agents. Voice and gesture-based input methods were also available for the creators to design natural conversations and body interactions with AI characters so that a more meaningful and equal relationship could be established between human and non-human participants.

As there are many types of interactions that can be designed in both fictional and non-fictional narratives, my exploration into relation creation concepts and techniques just marks the beginning of the field of relational experience design. Some of the techniques proposed in this thesis can be further expanded to work with more complex scenarios so that new forms of virtual relations can be created, but certainly, they will all depart from the foundational ideas laid out here. For that, I am eager to see the future of relational experience design, and I believe that more experiments and examples come out of the art and design communities.

8.2 Future Works

Following the investigation of my experiments, projects, and proposed concepts in relational experience design for immersive narratives, I close this thesis with my visions for the future. The first is about our social relations with others. Our social network over the internet will expand into an immersive space. More users will join and participate in this huge immersive social network. I see immersive technologies playing a role in helping us develop new relationships with people and with virtual communities in a more natural manner. The sense of co-presence brought by immersive technologies can help people build stronger social bonds, making them become more engaged with each other and promoting a more collaborative culture. At the same time, as I proposed in this thesis, non-human participants will also play an active role in this new immersive network. The newer interaction modalities brought by immersive technologies will be applied to interactions with intelligent agents. We will have 3D and spatial versions of chatbots that we can hang out with in virtual reality. The second aspect of my vision is that our networked social experience is going to have more immersive activities and more engaging interactive content for daily consumption. Just like our social media today, a large amount of user-generated content and daily life stories will be shared by users. Immersive technologies can help us experience someone else’s life story in a more embodied way, through a strong sense of direct engagement with the story content. A further step is that we will also be able to design and create our own interactive activities and there will be a huge new design space about the ways we can enjoy our time in an immersive environment.

These two aspects will be mainly driven by technological advancements as well as the need for virtual social interactions. They will also impact the community of artists. In the domain of art, immersive technologies will also enable new forms of expression and narrative content that the audience will be able to have strong mental and intellectual associations with. The sense of plausibility enabled by various meaningful interactions in virtual space will let the audience be more engaged and more convinced by the artist's storytelling, leading to new aesthetic experiences that we can hardly achieve today. On the other hand, the immersive network will also be a new place for artists to create, perform, and exhibit new relational art. Just like how today's relational art brings local communities together to reflect on our culture, politics, autonomy, and social relations, a virtual immersive version of that will also take place in the immersive network and create more impact than it has now. I am very optimistic to see the emergence of this new type of relational artwork and experiences.

Besides these broad visions, there are a few logical steps that we need to take to help make this happen faster. On the authoring side, we need to investigate no-code tools for immersive content creation. Just like how mobile apps and web apps can be created by drag-and-drop modules, a virtual reality experience may also be created in the same way that does not require any technical knowledge. An authoring tool that provides comprehensive authoring features is desirable for everyone to quickly and easily embrace the benefits of immersive technologies. Within the scope of no-code tools, immersive and in-situ authoring interfaces will also be in high demand. Such tools will help immersive literacy to easily demonstrate the power of immersive technologies to people with zero knowledge of augmented or virtual reality. On the general creativity side, AI-driven content generation methods can also help us be more creative about designing virtual environments, narrative plots, character behaviors, etc. Although existing tools such as Midjourney and Stable Diffusion heavily rely on existing creative outcomes from artists and may have copyright issues with their usage, we can start preparing for integrating future AI models into our creative pipeline to aid our composition process. They will further lower the bar of content creation, allowing the creators to build even more complex and plausible experiences.

If we look back at the past 30 years, we were mostly communicating and interacting with each other in a physical environment. No one probably expected the virtual aspects of our reality to take place so fast. Now many of us spend more time talking to others via digital communication channels through emails, text messages, photos, and videos. So for the next 30 years, we will likely be much more occupied by virtual reality. Perhaps, not only our relations with other people, but also relations with our daily objects, living and workspace, and the natural environment will all be enhanced and empowered by digital and immersive technologies. I hope this relationship enhancement will help us be more connected and more collaborative, creating a more empathetic humanity and society.

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