

In the Virtual Classroom: An Ethnographic Argument for Education in Virtual Worlds
Rebecca Nesson and Charles Nesson
Berkman Center for Internet & Society
Harvard Law School

The first day of Harvard's class on Berkman Island in Second Life was also the first day in Second Life for many of our students. We began with some simple orientation games designed to help students acclimate to the environment and to each other. In the game we called "Stand Up, Sit Down" I made statements to the class and they were asked to stand up (by pushing the "stand up" button) if they agreed with the statement and to sit down (by right-clicking on a chair and choosing "sit") if they did not. During that game I posed what I take to be the fundamental question, if a bit flippantly put, that those of us who propose to use virtual worlds in education must convincingly answer in the affirmative: "Is this real?" That question encompasses the main objection to using Second Life and other virtual worlds in education: that virtual worlds, at this stage of development, are really no more than glorified chat rooms, and very computationally expensive ones at that. The physical representation of space and self, the argument continues, offer at best a flashy but substantively irrelevant add-on to the educational experience and at worst a gamelike aura that distracts from the subject matter and detracts from the seriousness of the educational enterprise. The first small refutation of the fallacy of these objections came when a student (avatar name: USA Brody) answered my question in the negative:

[18:25] Rebecca Berkman: stand up if you think this is real.

[18:25] Yoyo Mah: What's real??

[18:25] USA Brody: In a limited manner this is real

...

[18:25] USA Brody: Because if you fell from a cloud in life, you would more than likely die...

...

At this point USA Brody flies into the air to a great height and (intentionally) crashes to the ground. He is unharmed.

[18:26] Yoyo Mah: lol

USA's use of the contrast between the basic realities of the physical and virtual spaces was our first demonstration of the potential to use our virtual environment as more than just a playful picture to accompany our discussion.

Yoyo Mah began our conversation by asking, quite appropriately, "What's real?" We carry a strong visceral sense of reality with us that seems to contradict the philosophical perspective that our reality is mediated (and perhaps constructed) by our sensory systems. Devotees of virtual life, by acting and interacting through an avatar, become comfortable with an alternative reality and an alternative set of sensory and expressive capabilities. Although at this stage of development, and perhaps necessarily, these senses and modes of expression are fewer and more rudimentary those we use to access our actual environment, they are not a strict subset. Though deprived of his voice, USA was able to express himself in Second Life in a way that is plainly impossible in his first life. As educators we can eschew the theoretical discussion of the nature of reality,

but in order to realize the potential of our virtual classrooms we must learn the lesson that USA's answer to the question offers. Rather than shying away from and minimizing the points of difference between our realities, we can incorporate them into our teaching. Three principles guide our attempts to do this: 1) use the technology for what it is good for and not for what it does not do well; 2) seek advantages in what appear to be limitations; and 3) where new capabilities are offered, find ways to use them. The representation of a physical space and of self and particularly the understanding of the interplay between the norms of related non-virtual environments and the virtual analogs are critical to the enhancement of the distance education experience that virtual worlds allow.

In what follows we describe our results from putting these principles into action in one course in Second Life, *CyberOne: Law in the Court of Public Opinion*. Education in virtual worlds is in its nascent stages. The first steps in understanding and method we offer from our short experience is intended to serve as a proof of potential and an argument for educators to apply their creativity and expertise to teaching in virtual environments. This paper will not be a theoretical one, but rather a practical, often ethnographically based, argument for the current value and future potential of virtual worlds in education that attempts to specifically address the concerns and reservations of the many thoughtful educators and observers who are not yet convinced. We take aim at the criticism that Second Life provides educators only with a fancy, heavyweight chat room. Working from our experience teaching in Second Life we argue that numerous seemingly small differences, often centered on the persistent and physical nature of the space, permit the creation of a class community in a way that has not previously been possible in distance education.

The Role of Reality

The analytical tool most useful to us in the design of our spaces and courses is a constant awareness of the relationship between the on-line and the off-line classroom spaces. Even for students and instructors who will never meet face-to-face in a classroom, the off-line classroom remains present. As we seek to take advantage of what virtual world technologies do well, we balance between incorporating the signals of the off-line space that allow us to take advantage of off-line social norms and discarding those norms in favor of new ones that are particularly suited to the virtual experience.

Students possess a strong shared set of norms about classroom configurations and behaviors, learned through years of schooling, that they bring to new class experiences. These norms help organize the educational experience by providing rules about when to speak, where to sit, when one can enter and leave the space, and more. The look and feel of a classroom signals to those present that the classroom norms are in effect.

One of the most powerful aspects of a 3D graphical environment like Second Life is the ability to easily recreate the signals that trigger social norms such as appropriate classroom behavior simply by creating a space that has the same look and feel as an off-line classroom. As an avatar enters such a room, even if she is new to the virtual environment, she finds that she knows a lot about what she sees around her and also about how she is expected to interact. Much of the instruction on how to use the space is therefore implicit in the knowledge that we bring from the outside. The experience of

corporate and other non-educational ventures in Second Life demonstrate that this incorporation of off-line expectations is both an advantage and a danger.

Media coverage of the use of Second Life by well-known corporations over the last two years shows two distinct phases. Early coverage showed an enamored if somewhat bemused cataloguing of the various and very impressive looking installations of businesses in Second Life (Siklos, 2006). More recently, articles such as “How Madison Avenue is Wasting Millions on a Deserted Second Life” in Wired magazine take apart this view as little more than fantasy as these corporate locations remain empty or sparsely populated over time (Rose, 2007; Boss 2007). Both the enthusiasm of the early articles and the writing-off of the technology in the more recent coverage belie a basic misunderstanding of what virtual worlds like Second Life do and do not offer.

Early corporate adopters tended to create virtual locations in Second Life that were impressive mostly for their faithful recreation of their off-line analogs. American Apparel, for instance, created a beautiful store replete with racks of colorful clothing that looked like an idealized version of its off-line analogs. Although these installations were impressive to visitors at first, they often proved ineffective at attracting visitors over time. They failed to take advantage of what the technology does well, limiting the avatar experience to a pale imitation of the analogous off-line experience. In the case of American Apparel, although an avatar could buy clothes, the simple styles that work in the off-line setting are too basic in Second Life where coveted clothes must do something more than just show off an avatar's figure.

These design errors have been widespread in attempts to transition businesses from the off-line world into Second Life. As Rose (2007) notes, many of the most prominent off-line life businesses have closed their virtual locations or let them languish with few visitors. Rose's conclusion is that virtual worlds may be little more than a trend with flashy graphics that amount to nothing. However, the existence of successful businesses in Second Life admit a more optimistic analysis. Design of an effective virtual location must emphasize what the technology does well, ideally even incorporating features that are impossible to realize in the off-line analog. It must also avoid replicating physical world features that lack meaning or function in the virtual world.

Although an admonition against replication of the physical world at first seems to be a clear design principle, observation of successful locations in Second Life shows that there is often utility to replicating elements of the physical world even when the replicated elements do not appear to have a function in the virtual space. Restaurants in Second Life provide an excellent example. Avatars do not need to eat for sustenance. However, many restaurants, coffee shops and bars exist and thrive in Second Life. This seeming paradox is easily understood when we look more broadly at the function of restaurants in real life. Providing food to customers is only one, and arguably not the primary, service that many restaurants provide. Rather, their primary purpose in many cases is to provide a structured social space in which the norms of social interaction are well-defined, widely-understood, and relied on heavily for certain common types of social interaction. Replication of a restaurant environment allows avatars to take advantage of their shared off-line social norms in their interactions.

Consider, for example, the role that restaurants play in providing a social environment for dating. A restaurant provides a neutral, semi-public location in which both participants feel safe. However, the social norms of the space limit interaction with

others in the space so that conversations can remain one-on-one and largely private. The interaction is time-bounded but flexible to a certain degree based on the type of restaurant chosen, the number of courses chosen, and the freedom of the diners to choose to linger or leave promptly. Simple conversation topics and reasons for comfortable silence are provided by the menu and by the food itself. Finally, the highly ritualized manners of restaurant-going give each participant a chance to evaluate their partner against a standard of behavior. Restaurants in Second Life cannot provide tasty food but they can provide all of these aspects of the structured social interaction. By replicating the physical world restaurant look, feel, and structured experience, they let avatars know that the social norms for off-line restaurants can transfer directly into the virtual experience.

Constructing an effective educational environment in Second Life requires careful attention to the balance between taking advantage of widely understood off-line classroom and educational practice and breaking from traditional educational expectations and practices when they do not work effectively in the virtual space. A direct translation of the off-line classroom experience works poorly because Second Life does not provide or provides less fluid versions of many of the modes of interaction and communication used in physical classroom settings. In these cases, the benefit of well-understood social norms must be weighed against the clumsiness of imitating off-line interaction in a less conducive setting. In many situations replacing an off-line mode of interaction with something that works better in the virtual environment is worth the additional cost of having to generate new norms of behavior. There are also certain types of interaction that are possible in Second Life that are not part of the vocabulary of the traditional classroom experience because they do not work well in the physical world. If the burden of acclimating students and instructors to them is not too great, they offer opportunities for enhancing the learning experience beyond what is possible in a traditional classroom setting. In the next section we explore the specifics of these trade-offs as we describe our application of these ideas in a virtual distance education classroom setting.

A Brief Introduction to CyberOne

CyberOne: Law in the Court of Public Opinion was offered jointly at the Harvard Law School and Harvard Extension School in the fall semester of 2006. Students enrolled in the course through the Harvard Extension School participated as distance education students. Live lectures given to the Harvard Law students were video taped weekly and made available publicly on our course website as well as on large screens on Berkman Island in Second Life. In addition to watching these lecture videos, Harvard Extension students met weekly with the professors as a group in Second Life for a classroom discussion or activity based on the lecture and material for that week. Classroom discussions took place on Berkman Island with an average of twenty students present at each meeting. As work for the course, Harvard Extension students formed groups of four to six students to work on a project within the Second Life community that required them to research an issue of relevance to the Second Life community and an active approach to creating change around that issue.

Virtual Worlds for Distance Education

Education at a distance is the most obvious educational application for virtual worlds. The typical distance education experience, though often quite valuable, still lags far behind the face-to-face classroom experience. The lack of class community, present almost without effort in face-to-face classroom environments, explains much of the difference in quality of experience. Students have less contact with their instructors, particularly in the informal ways that help to overcome barriers to free communication. Contact with fellow students is limited or nonexistent. The intangible but crucial social quality of a peer group, the opportunity to learn from each other, and the healthy and unhealthy peer pressure and competition that occurs in face-to-face classes is missing. The sense of responsibility and personal accountability engendered by direct personal relationships is weakened.

A lecture video can too easily go unwatched when there is no one to observe the absence. When students venture questions by email to their instructor, answers may take too long to arrive and may not sufficiently address the problem. Without a personal connection to the instructor, students may not feel comfortable asking for the help or extensions they need and instructors find it difficult to evaluate the validity of these requests when they do occur. The social, fun aspects of getting to know fellow students, commiserating with them about difficult assignments, and feeling the camaraderie of the class disappears placing an even heavier burden on the instructor and the material to be sufficiently engaging.

The asynchronous, placeless interaction provided by well-constructed websites, high-quality lecture videos, and interactive but still asynchronous discussion technologies like bulletin boards may adequately cover the substance of a course, but they rarely engender the interpersonal relationships that foster commitment, responsibility, and social stimulation. Synchronous and widely available technologies such as chat rooms appear to provide a solution by offering the opportunity for real-time interaction between students and their instructors. Yet in spite of their widespread availability, some distance education courses still do not make use of them. We argue that the persistent sense of place provided by 3D virtual worlds such as Second Life encourages the creation of a class community in ways that previous technologies, such as group chat, do not.

Our observations are the product of our own experience teaching in Second Life. We do not hope to draw sweeping conclusions from the experience of a handful of instructors and fewer than a hundred students over the course of a single school year. Rather, we present our work as one among the many nascent educational experiments that are occurring in 3D virtual worlds. As we might say in computer science, we offer this to the reader as “a feature, not a bug.” We made our choices and our observations carefully, yet they are necessarily only first steps and deal primarily with the most basic elements of a classroom experience. A dizzying array of possibilities for education in virtual worlds remain untried. Yet, even these first experiments made believers of us: the advantages of using virtual worlds in distance education are real and substantial. If the advantages can become apparent to the relative novice, we can only imagine what may lie ahead as more educators turn their attention to realizing the potential of virtual worlds in distance education.

Fancy meeting you here

The residential college campus provides a persistent communal space where students and professors meet formally for classes and informally in libraries, dining halls, quadrangles and dormitories. Simple interactions such as conversations in the minutes before class begins and after it wraps up, walks from one class to the next, and chance meetings in the library and student center are frequently the basis for forming new relationships and sustaining existing ones. The space provides a sense of belonging and a place to go where one can work individually or in a group, but always in the midst of a peer environment. The connection to the college as a place and a community helps students by making them aware that they are part of something bigger than themselves, providing them with reminders that other students are working toward a similar goal, and offering the substantial support membership in a peer group can provide. None of these things bear on the substantive course material of a particular class, but all contribute to the successful experience of an enrolled student.

A virtual campus that provides a persistent sense of place and a platform for the formation of interpersonal relationships and a commitment to the collective experience offers the missing piece in distance education. The elements of a virtual campus that allow it to successfully serve this purpose are still up for debate. Some aspects of the traditional campus, such as classrooms and open spaces for informal gatherings, translate very well into the virtual environment. Others, such as libraries where students might go to do their work, still await changes in the 3D virtual world technology that make it possible and desirable for students to simultaneously exist in a virtual world and work on homework that requires use of other software such as PDF readers, word processors, or web browsers. What is clear is that in order to serve the community building functions we envision, the virtual campus must be an inviting place to which students have both desire and good reason to come.

Berkman Island, Harvard's campus in Second Life, has a distinct campus-like look with beautiful stone classroom buildings and well-maintained outdoor spaces where students congregate. Sun shines on manicured grass and seating areas where groups of students and teachers gather. Stone paths guide the visitor around beautiful buildings and over the historic Weeks footbridge on the Charles River. It looks and feels like Harvard all dressed up for graduation day. Although the effect of the look is impossible to measure, it does project a message to visitors. The replication of Harvard buildings and landmarks and the idyllic college campus feel makes it easy for visitors to believe that Berkman Island truly does represent Harvard in Second Life. The look and feel of the island challenges visitors to take it seriously. Much like on the actual Harvard campus, most visitors do: tourists walk around and often take pictures, students congregate and participate in student activities, a few irreverent locals use their free access to the campus as a chance to thumb their noses at the hallowed halls.

The material point is that the design of the space conveys a message to the visitor about the nature of the space and the expectations of how it will be used. That message will be understood in the context of the experience of the visitor. With Berkman Island as most visitors' first encounter with a university in a virtual world, the message of the space critically conveys both the seriousness of the enterprise of education in virtual worlds and one version of the collegiate campus ideal.

No matter the beauty and charm of the look of the virtual campus, if students do

not have a reason to spend their time there, they will be absent. We use the simplest methods to help draw students to the campus and keep them coming back. First, we hold class meetings and office hours in Second Life on a regular basis. Second, we make course lecture videos and other materials available in Second Life so that students may come to Berkman Island to watch the lectures by themselves or with other students. Third, we assign out-of-class work that requires students to come into Second Life to complete it. For example, this might consist of individual assignments that involve research in Second Life, or construction of presentations that will be made in Second Life. Fourth, we ask students to work in groups in Second Life either on projects or for the purpose of discussion of course materials. Fifth, we maintain a public sandbox—an area where anyone can come to practice building—on the island so that it is unusual to arrive on the island and find oneself alone. Finally, we open as many of our activities as possible to the interested public to help build a group of Second Life residents who feel a connection to Berkman Island and come to participate in activities, meet their friends, and offer help to students and other newcomers.

Once students are on Berkman Island on a regular basis, they begin to form the network of relationships that support them and encourage their commitment to the enterprise. Students pointed to having the chance to get to know their classmates outside of the formal classroom setting as a major factor in their enjoyment of and connection to the class experience.

How do I look?

One of the potential advantages of online communities is the absence of bias based on looks that pervades our day-to-day offline existence. Students and instructors in face-to-face classes are subject to the judgments of others on the basis of sex, age, race, accent, the style and quality of our clothing, and so on. In a chat room or on a bulletin board we are freed from these constraints. Identified only by a short handle—say, rn2007—others are constrained to judging us on the basis of what we say.

We are well-trained in making judgments about others based on visual and social cues that are hard to represent in a text-only environment. As actors in a face-to-face social setting, we are experts at representing ourselves to our peers (and students) in a way that conveys a message about who we are. We are also astute readers of the signals sent by others. We convey substantial and varied information with our facial expressions and physical appearance that others use in their interactions with us (Donath, 2001). When we enter a text-based chat room we find ourselves stripped of a substantial part our usual means of communicating our own personalities to others and of understanding who the others are around us. Second Life permits us to regain much of that mode of self-expression in a fanciful way (Smith, Farnham & Drucker, 2002). When a student creates an avatar in Second Life, there is no requirement that it must look like her. She may freely choose an expression of herself that tries to communicate to her peers whatever qualities she seeks to display. Her choices are, of course, not free of the biases that exist in our society. The avatars she encounters all have actual people, with all of their biases still intact, behind them. Additionally, she must determine how a particular social cue, now free from the constraints of reality, will be interpreted in this new environment. The value of being tall, thin, young, and pretty is plainly diminished when all it takes is the

click of a button to achieve it. However, simple statements such as the choice to wear a Captain America-style suit, to be a robot or animal rather than a sexed human, or to make her avatar resemble herself as much as possible communicate quite a lot of information.

On the first day of class in CyberOne we all met a student in a Captain America-style suit, a fox-like creature on stilts, a small bearded man in a wedding dress, and quite a few cookie cutter avatars that had not yet been modified from their standard look. Students with a different look drew immediate comments. Others wanted to know where they got the outfits, how they put them on, and why they chose them. Even before class had begun, this simple point of conversation had broken the ice and the students had begun to form relationships. As the semester progressed and the students became more comfortable with the Second Life interface nearly every student customized his/her avatar to better express some representation of his/her self. When students arrived with a new look or a new outfit, it was always cause for conversation.

In the Classroom

The discussion technology in Second Life is often singled out as one of the major shortcomings of the environment when compared to a face-to-face classroom experience. Although voice chat is possible for small groups it is often not practical due to technical constraints and was not yet available in Second Life during our course. At the present time most communication still takes place via a chat or instant message interface. The challenge of leading or participating in a discussion in a chat environment is daunting at first. Because of the time it takes to compose a comment, students and teachers alike offer shorter and less subtle, detailed versions of their ideas than they would if they could speak them. Also due to the time it takes to compose a type-written comment, it is too cumbersome to wait for another person to finish speaking before offering one's own ideas. As a result, classroom discussions generally have several threads that participants must sort out. The experience is quite overwhelming and can easily be disheartening to student and teacher alike.

Our disorientation comes from more than just the steep learning curve of a new environment. As students and teachers we have become accustomed to a fairly rigid set of classroom behavioral norms that we began to learn in our earliest classroom experiences. For example, students are supposed to wait until recognized by the instructor before they speak. Entering the classroom environment in Second Life, students carry these norms with them. Because this method of interaction does not function well, we must unlearn the usual classroom behavior and replace it with a new norm for the virtual educational environment.

The challenge to establish new norms where necessary extends beyond discussion. Some skills that were valuable in a face-to-face classroom, such as lecturing, are no longer feasible or effective. New skills, such as moderating a multi-threaded discussion so that it remains on topic and coherent, must be mastered. The old norms have to be discarded explicitly so that students feel comfortable speaking "out of turn". With a little perseverance, a new form of classroom interaction emerges and the initial discomfort with leaving the old classroom norms behind is replaced with the surprising realization that in some respects, the new norms are superior.

Anyone who leads discussion sections in face-to-face classrooms is well aware of

the challenge presented by two ever-present types of students. First, there are students who rarely, if ever, speak up even with substantial encouragement or cajoling. Second, there are students who rarely, if ever, cede the floor to others. Discussion in a text-based environment quite cleanly addresses both of those problems.

One of the reasons why some students remain quiet in class is the feeling of anxiety produced at the moment at which they are called on speak. Consider a student who never speaks in class who is called on to offer an opinion. All eyes in the classroom turn to focus on him. He is required to produce, in a sense to perform, a fully formed idea in spontaneous speech in front of all his classmates. For many students this pressure is sufficient to silence them. In Second Life, this pressure is removed. Students pre-compose their comments before they enter them into the conversation, giving them the opportunity to think carefully about what they want to say and how they want to say it. They have complete control over when the comment is entered into the discussion. Perhaps most importantly, to the extent that anyone gazes at the speaker, it is his avatar, not him, that is the focus of attention. These observations were borne out by students' reports of high levels of comfort speaking in class in their written evaluations of the course. These and perhaps other factors helped CyberOne to be the most broadly participatory discussion class we have ever offered in a face-to-face or distance environment.

Consider, on the other hand, the student who takes up too much airtime. An instructor may feel the need to interrupt a student who speaks too often or too long. The text-based, multi-threaded discussion environment of Second Life again solves the problem. A student may speak as much as he likes without ever reducing the opportunity for others to contribute to the discussion. The lack of the social norm requiring turn-taking makes this possible. Even when a student does occupy a large part of the chat, it is easy for others to sort through the discussion and give at least equal attention to the comments of others.

An obvious question is why these same benefits do not seem to exist in simple text-based chat room environments that have long been available to distance educators but are rarely used. Several factors distinguish the experience of discussion in Second Life from the usual chat room experience. Lack of representation of presence of the conversational participants is often identified as the major shortcoming of text-based chat environments (Viegas & Donath, 1999). In a classroom setting where there may be anxiety about speaking up, this can result in the appearance of a nearly empty classroom with the conversation dominated by the instructor. This visual "silence" can be a deterrent to students entering the discussion. Second, as documented by Brown and Bell (2004), the existence of a shared view of each other as well as of objects and resources within the environment provides a context for the discussion, making discussion flow more easily. Although Second Life does not provide an ideal chat interface in many respects (Viegas & Donath, 1999), the representation of avatar presence makes preferable to the text-based alternatives.

Making Use of Computation

Group collaboration and decision-making is a major challenge in a text-based environment. Students working in groups for CyberOne struggled with it throughout the

semester. They found that it took an inordinate amount of time to hear everyone's ideas and that it was difficult to figure out their points of agreement and disagreement. The work of coming to agreement is harder both because of the difficulty of communicating in often non-linear multi-threaded text and because of the lack of other useful cues such as head nodding, eye gaze, and facial expressions. Although these physical cues can be incorporated into Second Life, they are currently awkward to use and they require a level of facility with the interface that one cannot assume all students possess. Making the erroneous assumption that every avatar would be nodding its head if it agreed leads to an even greater difficulty making a decision when some people are not making use of those cues.

David Johnson (2006) points out, however, that when we enter the realm of virtual worlds we have the computational power of our computers and the graphical rendering ability of the 3D worlds to help make up for the subtleties of expression that are unavailable to us. Our computers are good at synthesizing complex data and the graphical environment of Second Life provides many options for representing the synthesis so that it is easily comprehensible to a group. Thoughtfully crafted tools can take advantage of these features of the environment to lessen the burden on groups and decision-making. Tools such as those developed in the Information Spaces project at the MIT Media Lab (<http://web.media.mit.edu/~dharry/infospaces/>) or the Question Tool developed at the Berkman Center for Internet & Society (<http://cyber.law.harvard.edu/questions/chooser.php>) provide good examples.

Conclusion

In one short year we have matured from newbies in the Second Life environment to advocates for its (already partly realized) enormous potential for use in education. The advent of a persistent, compelling virtual place allowed us to create a class community that has never before been possible for distance education students. The ability to open the course to the public at large in a separate, virtual space gave hundreds of people the chance to participate in our course for free while arguably improving the educational experience of the enrolled students, maintaining the value of their degrees and transcripts, and promoting the ideas of the course beyond the university walls. Although there is cause for worry about universities continuing on the present course in their relationships with Linden Lab, there is also cause for hope if universities work together to negotiate for what they want or build it themselves.

With each new technology that appears there is a rush to try to incorporate it into recreation, communication, business, and even education. There are always those who argue that the new technology is a fad and those who regard it as a panacea. Virtual worlds are no exception to this rule. Virtual worlds have too much promise and demonstrated utility—at the very least for the games that are played in them by millions worldwide—to succumb to the doubts of the naysayers. However, putting them to good use in business, education, and other fields cannot be accomplished simply by transplanting real life norms and modes of interaction into the virtual. With attention to the particular qualities of virtual spaces and modes of interaction and creative and open minds, we can avoid the pitfalls of clumsy applications of the technology such as 1) transplanting a physical world practice that cannot be done as well in the virtual world

due to the constraints of the technology, and 2) mimicking aspects of the physical world that have no purpose in the virtual world. Instead we can use the technology to evoke familiar norms and put them to use while also creatively moving beyond the limitations of the physical world constraints of space and physics.

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