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ADAPTATION IN VIRTUAL WORLDS

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ABSTRACT
In collaboration with scientists, engineers, sociologists and designers, we have developed virtual worlds for the visualization and interaction with dynamic systems. This allows participants to interact with three-dimensional structures that constantly change and adapt through time. Participants can use simple building blocks to manipulate three-dimensional structures in real-time, allowing them to interact with systems that constantly change and adapt over time. This paper analyses the source and role of change in dynamic systems using virtual reality; particularly the role of constraints and transformations that can generate real-time adaptations of a virtual system. We propose a new design process that allows participants to collaborate with virtual agents. The goal of this process is to create accurate dynamic three-dimensional systems that can self-adapt under constraints and evolve into new spatial configurations as a result of adaptation. The collaboration between participants and virtual agents offers new perspectives on user interaction, dynamic three-dimensional manipulations and about the evolution of a virtual architecture inside a virtual world.

KEYWORDS
virtual worlds, visualization, interaction, adaptation, complex systems

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From architectural representations to virtual spaces, building a three-dimensional model allows us to visualize static and dynamic elements of the world around us. Traditional models use building blocks to mimic our perception of the real world using familiar materials. «Large room-sized models, made from, for example, wire, plastic, brass, balsawood, and plasticine, were used to refine and represent protein crystal structures [...]» (O'Connor et alii, 2018). One of the goals of a traditional model is to organize a large amount of information and knowledge in a spatial way. «Can we integrate what people and computers respectively do well? We would like to maximise the effectiveness of this human-computer symbiosis, to find places where computational power is most useful and where human ability is best applied?» (Cooper, 2014, p. 42). Buckminster Fuller is one of the pioneers of experimental three-dimensional design exploring the intersection of information architecture, dynamic structures and human interactions. He created the 'tensegrity' structures, a non-traditional approach to building a three-dimensional structure that involves a reversal in perception. This was also an attempt to visualize the coherence of a structure where thin tractive cables replace a compact mass (Krausse and Lichtenstein, 2017).

Virtual cameras, storytelling and virtual reality experience | In 1972, Charles and Ray Eames explored the use of abstract animation and in-camera visual effects techniques film to visualize the SX-70 Polaroid, a groundbreaking photographic camera. The movie shows how people could take photos with the SX-70 in almost real-time by processing a print, instants after the picture is taken (Fowler and Crist, 2012). The viewers of Charles and Ray Eames' movie can discover a process that someone can't see but the effects are visible by everyone. The Eames movies are early examples of breaking down our complex perception of reality into simple building blocks. Filming a virtual world with a virtual camera using lines of code is a similar process. A virtual three-dimensional model can be visualized through a virtual camera which renders space and time at various scales and speeds; something that would be difficult to achieve with a physical or mechanical simulation. Virtual models often use sensing and our perception of reality as a reference for accuracy and precision.

Virtual reality enables participants to move between different scales or to switch between systems seamlessly 'without changing course'. Participants can move randomly from the detail of one virtual object to a multitude of virtual objects seen in their context – in the same space and with a continuous camera move. The virtual camera, moving at 90 frames per second, dances seamlessly following the paths desired by a viewer. The cinematography of the movie Children of Men created by Emmanuel Lubezki uses a similar camera movement through innovative single-shot sequences. To 'create the illusion of a continuous camera move' by combining 'several takes to create impossibly long shots' with a 'seamless blend'. Cuarón and Lubezki created Carne y Arena, a virtual reality installation that premiered in 2018. «The important thing is how you blend everything and how you keep the perception of a fluid choreography through all of these different pieces» (Cuarón cited in Debruge, 2007). Cuarón and Lubezki created Carne y Arena, a virtual reality installation that premiered in 2018.

For the Dynamic Virtual Protein project (Gauthier, Patel and McGrath, 2019), a virtual camera can travel from the atomic scale to the molecular scale of proteins living together in a 'soup' which is a biological eco-system (Fig. 1). This illustration shows a live virtual reality performance of the building of a virtual protein. The virtual world enables the participant to explore a virtual protein regardless of the scale of the visualization. This is different than previous molecular visualization which often lacked continuity when changing scales and often required a change of models in space and time.

When we experience a virtual city or a virtual character, we discover that the shape of space has a history and tells a story. A virtual city or a virtual character are dynamic systems in constant transformation and evolution. Their dynamic three-dimensional structures reflect current adaptations and mutations and ones that were inherited from their own history. The backstory may include past conflicts, disruptions, resolutions and destructions. We found a similar problem when recreating virtual of proteins, which are the smallest units of life inside a human cell (Schrodinger, 1944). The prediction of the spatial structure of a protein from its amino acids is still a mystery after decades of research. Although we know the sequence of amino acids of a protein, we don't know the steps that transform the sequence into a three-dimensional structure in space. How folding and binding happen is still a mystery (Pauling and Corey, 1951). All attempts to form a slightly different three-dimensional structure may result in an inactive protein that disintegrates to atomic chaos. Chances of mutation by disrupting the spatiality of the protein are statistically very rare. But success will take the activity of the protein to another level.

In many different contexts, virtual reality experiences are used to facilitate someone's experience of what is possible or of creative hypothesis. Sutherland describes the possibility of the creation of new digital modeling paradigms to visualize and understand both 'familiar' and 'non-intuitive' ideas and concepts. «The ultimate display-would, of course, be a room within which the computer can control the existence of-matter. A chair displayed in such a room would be good enough to sit in» (Sutherland, 1965, p. 506). Virtual reality has been used with models where participants can engage with invisible mechanisms of dynamic systems. Participants can easily visualize spaces at different scales in time and space; from nanoscale to molecular and whole ecosystems. Specifically, participants immersed inside virtual worlds can accelerate the rate and scope of observations. Making creative hypothesis and manipulating and interacting with the elements of the virtual world, is a fundamental element of the experience. You can 'sense' elements of the virtual space and the forces connecting elements in the space. Lanier, a pioneer of the virtual glove in virtual reality writes «Input is more important than display. Your input in VR is you» (Lanier, 2017, p. 127).

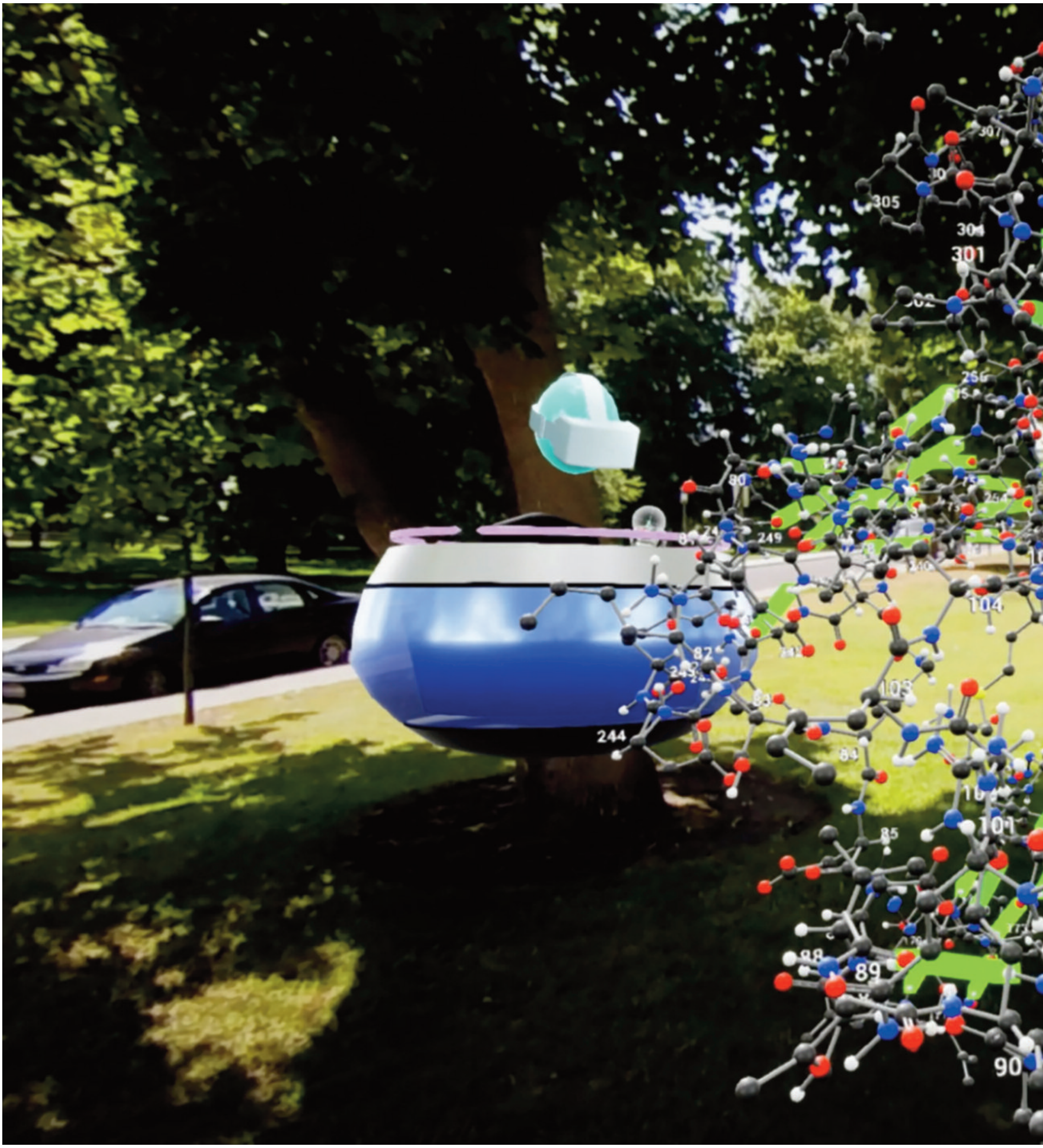
Spatial structures of complex systems | The three-dimensional structure is often a critical element of complex systems, such as the brain, living organisms, social systems and ecological systems. Predicting the functional organization of a system's spatial structure just from a few pictures is a puzzle difficult to solve. Generating a virtual city remains an on-going three-dimensional computational problem with unsolved questions. For example, how can we visualize the overall spatial design of a virtual city based on a collection of pictures of its buildings? Virtual character design faces similar conceptual problems. How can we visualize the kinetics of a virtual character from a map of its pathways and obstacles inside a videogame?

For many types of biodynamic systems, adaptations and mutations are often irreversible. Biodynamic systems are rule-based unlike not control based physics systems. This means that they cannot be disassembled into small building blocks like mechanical systems based on physics. Once they are broken into sub-units, they cannot be visualized as a whole dynamic system. Take for instance the brain, if broken into pieces it will not function as a whole 'brain' anymore as the full network of connections between the regions of the system is lost. Biodynamic systems must be studied as intact systems. When the integrity of a dynamic system is compromised or disrupted, biodynamic systems will try to survive by maintaining their state of equilibrium or low energy level, through adaptation or mutation.

Biological systems are rule-based. The difficulty with eco-systems and biological systems is that when we disrupt them, we basically change them. After trying to trace the lineage of every cell in a worm's body Robert Horvitz said: «It was exhausting, hallucination-inducing work, 'like watching a bowl of hundreds of grapes' for hours at a time, Horvitz recalled, and then mapping each grape as it changed its position in time and space» (Mukherjee, 2016, p. 191).

Control-based systems are the most common type of dynamic systems that participants encounter in a virtual world. A basic physics engine includes gravity, collisions, accelerations and speed. It is far more simple than rule-based systems. In the case of a river's watershed, a control-based system including the hydraulics inside the watershed is very predictable and can be easily broken down into sub-systems: the flow of water, the collisions with rocks and other rigid obstacles. The cohabitation between two dynamic systems may often be invisible to the human eye (Fig. 2). A school of fish in the river is a rule-based system based on the randomness and density of the fish. The squares in the background of Figure 2 represent a dynamic control-based system that can be a watershed or the construction of a new road or bridge. The power of seamless continuous visualization using a virtual camera allows to transition from a virtual fish swimming in the river to the scale of the whole watershed of a river.

Heterotopia and adaptation | Foucault's definition of Heterotopia is a space where change can unfold and grow within it (Foucault, 1967). It includes situations visualized in virtual spaces where participants can interact with information, biophysics,



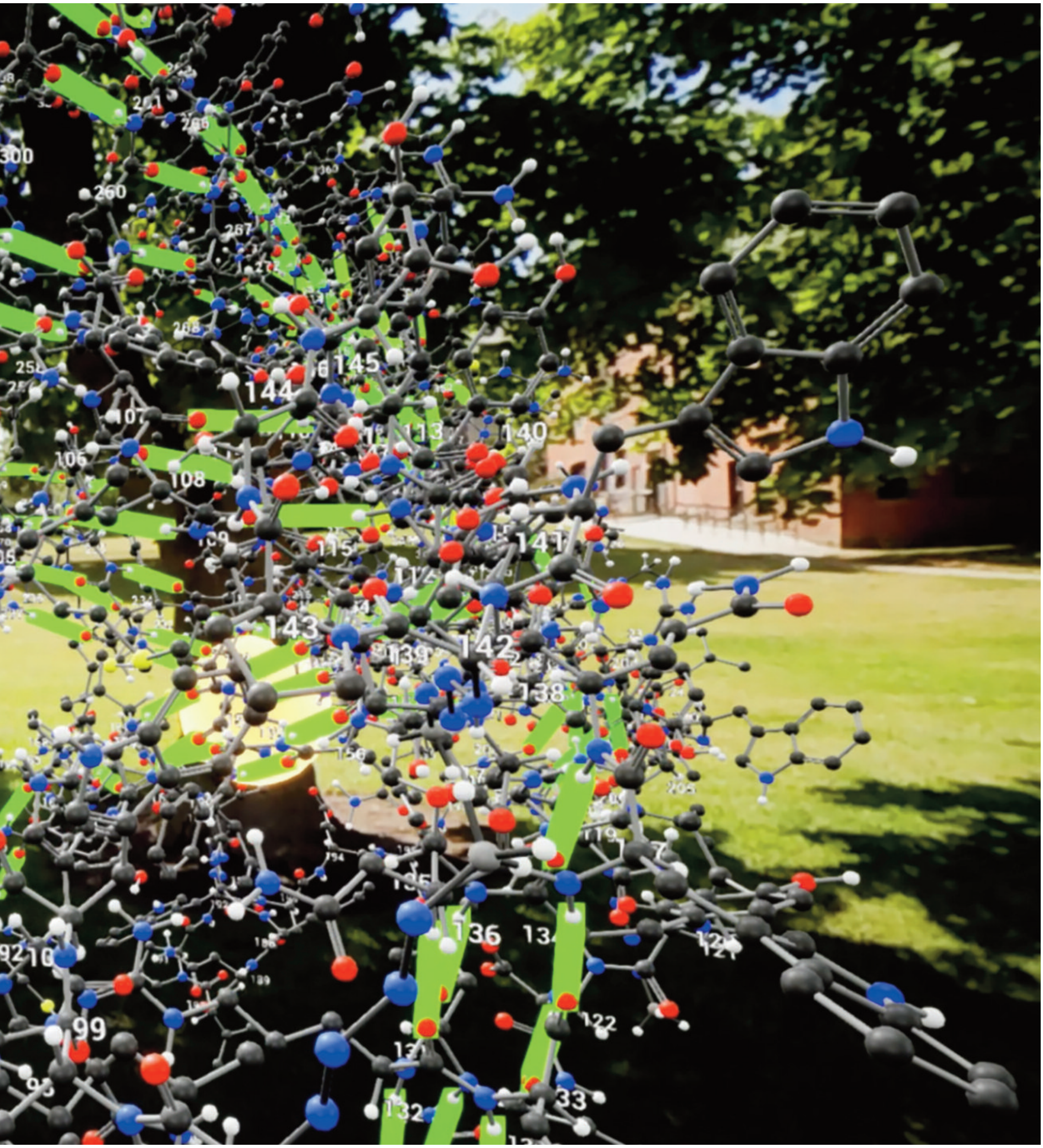


Fig. 1 | Dynamic Virtual Project showing a virtual reality participant (visible on the left side of the illustration) manipulating a virtual protein in order to explore dynamic changes of the three-dimensional structure of the molecule. The participants use a mixed reality head display that allows them to see trees and buildings of their surroundings while working on a virtual protein at the atomic scale (Snapshot of the Dynamic Virtual Protein Builder, virtual world created by J.-M. Gauthier and I. McGrath, 2019. Research project by J.-M. Gauthier, J. S. Patel, and I. McGrath, funded by a National Science Foundation grant award OIA-1736253 ‘RII Track-2 FEC’).

ecology and energy systems. Heterotopia in a virtual space would follow these active principles: 1) Starting with an event, a disturbance, disruption or new idea; 2) Some participants interact with dynamic systems inside a virtual world as they see the event as a prospect for developing a novel reality; 3) A risk mitigation system provides feedback and readjustments of the systems inside the virtual world. Feedback is based on the difference between real-world data and data from the virtual system.

Marcos Novak revisited and expanded Foucault's concept by building TransTerraFirma a groundbreaking virtual world that initiated a quest for fluidity and plasticity in virtual worlds. He defined Liquid Architecture as 'an architecture whose form is contingent on the interests of the beholder'. He envisioned the possibility for new types of interactions taking place in virtual worlds. He defined the role of disruptions from new ideas and concepts that constantly reshape the design of virtual worlds. «Liquid architecture makes Liquid cities, cities that change at the shift of the value, where visitors with different backgrounds see different landmarks, where neighbourhoods vary with ideas held in common, and evolve as the ideas mature or dissolve» (Novak, 1995, p. 34).

Following Novak's ideas and concepts, we can redefine the design process of Heterotopia as a virtual space of novelty and change. Although a virtual system is in a state of equilibrium at the time of its creation, big and small variations will actually create fundamental changes for the whole virtual world. When designing a virtual biosystem, our goal is to design forms of adaptation that will lead to permanent mutations. For example, a biological mutation or in the case of a system that is alive or a social system, a form of adaptation, that can move the system to another level. Adaptations create responses that change the system and take it to another level of equilibrium.

Designing adaptive systems in virtual worlds | Following are examples of virtual worlds assembled and built-in real-time – on the fly – using big-data flowing into a virtual world. Each illustration of a virtual world is presented as an example of heterotopia, a virtual space of resilience (McKnight, 2013). Some active principles of adaptive systems inside virtual worlds are: managing feedback, maintaining diversity and redundancy, managing connectivity, fostering complex adaptive systems thinking, encouraging learning, broadening participation, and promoting polycentric governance systems (Cilliers et alii, 2013). The virtual worlds share similar requirements such as crossing the boundaries of scale, being interdisciplinary and evolving as dynamic systems.

For example, a change of water temperature inside a virtual river will affect the distribution of fishes and accelerate certain mutation of their locomotion systems. The process of real-time virtual world-building is illustrated by the superposition of two dynamic systems: a school of fish, an animated bio-system following the fish's behaviours and a control-based water system following fluid dynamics. When the participants interact with the dynamic systems by changing the temperature of the water, the effects are visible. The virtual worlds can show a form of adaptation of a school of

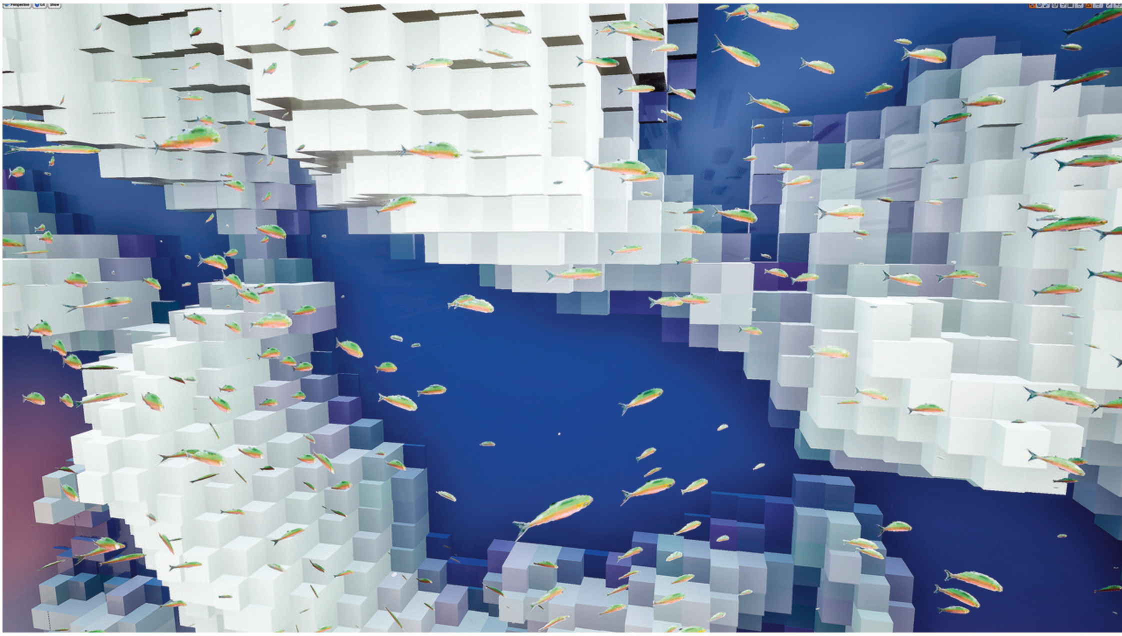


Fig. 2 | Things that usually invisible to the human eye are made visible. For example, the cohabitation between two dynamic systems. A school of fish is a rule-based system based on the randomness and density of the fish. The cubes in the background represent a dynamic control-based system that can interact in real-time with changes of water temperature or velocity inside a watershed during the construction of a new road or bridge. If you imagine the scale of a fish or the biophysics of a real-time virtual fish swimming in the river compared with the scale of a watershed, you can grasp the power of seamless continuous visualization using a virtual camera – video at: vimeo.com/370775895 (Snapshot of a dynamic virtual river created by J.-M. Gauthier and I. McGrath, 2019).

fish to the change of temperature by reaching a new equilibrium that allows the system to carry on. I describe dynamic virtual systems where feedback is the result of the difference between adaptation and a conservative approach. In other words, a positive feedback will spin the system into a new level of equilibrium. A negative feedback will move the system to a lower level of energy, maintaining the stability of its organization at all costs.

My goal as a virtual world designer is to allow the spatial growth of heterotopia and to create 'liquid experiences' inside a virtual space. The design process usually starts with storyboards of case studies inside a large ecosystem. Storyboarding clarifies contradictions, collisions or intersections of spatial systems and their expression in space. This is a bit like studying car traffic in a city. If you consider the pedestrians – they belong to a different spatial system but they intersect the car traffic. We visualize the dynamic exchanges between the two systems and how they self-regulate themselves. Virtual designers use the storyboards to generate the spatial form of a world based on the equilibrium between several systems.

It is really important to present a virtual world where the initial conditions are a state of equilibrium. The next step is to test the equilibrium of the system by bringing disruption or a certain level of chaos. As we poke the system somewhere, we want to see how it readjusts and adapts to a disruption. Of course, there are many ways to do that. You can fake an adaptation by scripting all the reactions. Or you can try to introduce enough complexity in the system so that its reactions change according to a set of parameters. The main goal is to create a form of adaptation that will lead to a mutation. For example, a biological mutation. In the case of a system that is alive or a social system, we can generate a form of adaptation, that can move the system to another level.

Temperature is one of the first elements that can change and affect a biological system or take it to another level. When the temperature rises, the effects on the ecosystem of a river can be irreversible. Fish begin to migrate somewhere else or they develop mutations.

Collaboration with virtual agents in virtual worlds | Research on disruption and adaptation in virtual worlds leads to the design of virtual agents who can collaborate with humans to solve complex problems. Virtual agents dialogue with a human participant to adjust his or her interactions so they can be accurate inside the virtual world. They can process spatial data with great speed and precision and act as a liaison for both the virtual world and a human participant. They can correct transformations that could be impossible in a real-world, helping someone working with accurate spatial data.

For example, when a participant creates a mutation at the nanoscale level inside a virtual protein, a virtual agent may say ‘No, what you are doing is really not possible’ or ‘you are putting things upside down – let me correct that’. Presently working on automated interactions, these virtual agents perform like virtual drones or virtual robots to help in a participant’s work (Fig. 3). Real-time human-assisted virtual agents offer a new field of spatial interaction where participants collaborate with automated virtual agents in order to design sustainable forms of adaptation. Although manual and automated processes use similar sets of manipulations and attributes, the automated process has greater accuracy, is extremely fast and can process unlimited number of virtual objects of a virtual world – one-by-one. The use of virtual agents is part of human-machine interaction developed by NASA for mission control and Extra Vehicular Activities – EVA (Sierhuis, Clancey and van Hoof, 2007). They offer great possibilities for the visualization of adaptations inside of a dynamic system.

Researchers are using the collaboration between humans and robots in smart environments for mission planning on Mars or other planets. (Sierhuis et alii, 2009) They create teams where astronauts collaborate with robotic devices. For example, what if the survival of a robotic device is compromised by the actions of a human. This creates a new system of communication which is actually the basic architecture of a collaborative virtual world. Virtual agents can perform high precision data-driven tasks. Each agent receives data from a specific channel. We have tested – and had success

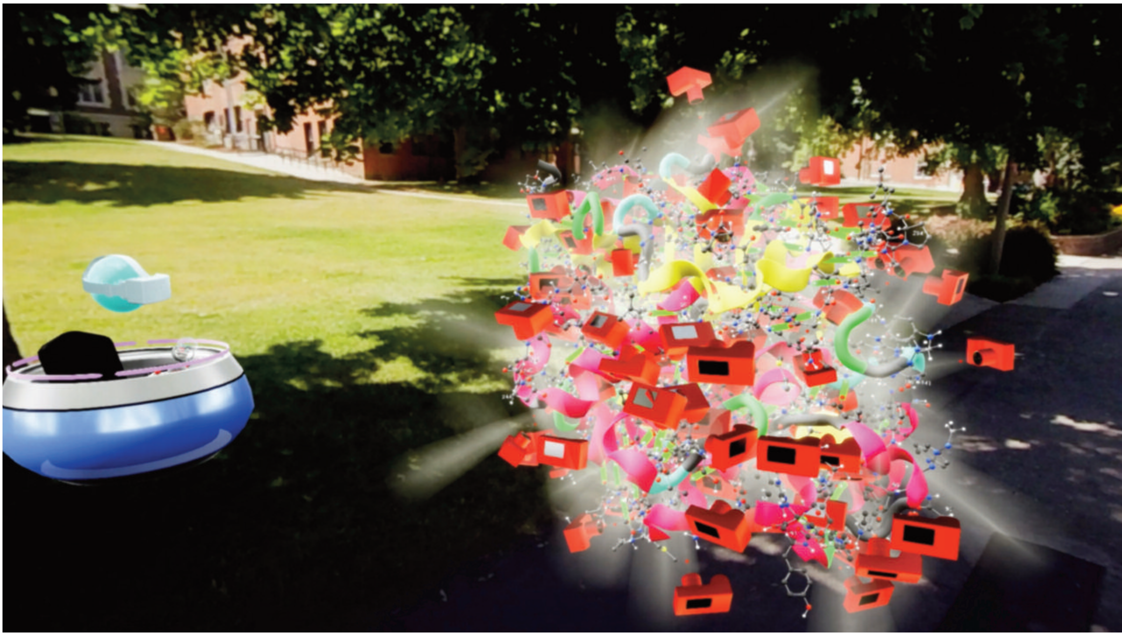


Fig. 3 | Dynamic Virtual Project showing a building a virtual Beta-lactamase protein. The three-dimensional structure of the virtual protein is assembled by a swarm of virtual agents – the red boxes visible in the middle of the picture. Building and exploring the three-dimensional structure of a complex virtual protein is a long and complex process at the nanoscale level. One of the participants – the avatar with a virtual reality headset visible on the left – receives the help of virtual agents which are fast and accurate (Snapshot of the Dynamic Virtual Protein Builder, virtual world created by J.-M. Gauthier and I. McGrath, 2019. Research project by J.-M. Gauthier, J. S. Patel, and I. McGrath, funded by a National Science Foundation grant award OIA-1736253 'RII Track-2 FEC').

with – a 'grab and drag' and a 'push-pull' virtual agents programmed to perform three-dimensional tasks. The virtual agents can work together, compete and/or equalize their mutual forces of attraction or repulsion in order to create a default shape of a complex virtual structure. Our current research focuses on many questions related to adaptation and communication in the virtual world. For example, what will be the new look and feel of a dynamic system after a major software update of a virtual world? This can lead to major changes during the sequence of collaboration with a human. How will a virtual agent communicate about these changes? Will the behaviour of a virtual agent change overnight?

An application, the Virtual Protein Builder | The experience of assembling and organizing three-dimensional models in virtual reality can help to make sense of complex spatial relationships in the natural world. The Virtual Protein Builder is a virtual world that enables a new type of interaction between scientists, college students and high school students working on proteins. Experimental three-dimensional models provide structural insight but lack the often non-intuitive mechanics that allow molecules to move and flex. Unfortunately, the human eye cannot see a protein directly in vivo. This challenge requires an unusual mix of precise and rigorous approaches on the side of the scientists and a three-dimensional vision from an artist. Though the visualization of protein is often accurate, it can also be frustrating because the representation of the information is incorrect or oversimplified.

Virtual agents inside virtual worlds have applications in education. For example, virtual agents can correct the work of a participant or reorganize what they are doing by injecting accurate data from the real world. Virtual agents can help someone who is trying a new hypothesis by relocating elements that are a little bit away from their real locations. When testing visualizations of bio-proteins, with undergraduate students, they often start with little knowledge of the topic. The students interact with the virtual agents and learn by watching them build a protein. When working with scientists, the process is completely different. The scientists want to work with the virtual agent to create complex virtual protein systems. By utilizing different strategies of the evolution of virtual worlds, elements can be included for the visualization and interaction with dynamic systems. We reviewed several examples based on accurate simulations of virtual worlds. The methodology used to build the virtual world allows to visualize and interact with virtual objects of various scales and in the context of environments with increasing levels of complexity. The design process opens new ways to study virtual mutations and to simulate adaptation inside a virtual world.

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