Arguably augmented reality : relationships between the virtual and the real

Schraffenberger, H.K.

Author: Shraffenberger, H.K.
Title: Arguably augmented reality : relationships between the virtual and the real
Issue Date: 2018-11-29

5 From Imitative to Imaginative Realities: Influences and Interactions Between the Virtual and the Real

AR allows us to experience virtual objects in our otherwise real environment. These virtual objects can not only passively *exist* in otherwise real the world, but they can also *act* in and *interact* with this world. For instance, a virtual ball can seemingly collide with a real wall, and a virtual toy can sense and react to its owner (see chapter 4). In this chapter, we take up this idea of virtual-real interactions and examine how the virtual and the real can influence each other in augmented reality. We explore whether and how real objects can affect virtual objects and vice versa.

Our exploration is driven by our own curiosity and imagination. We envision scenarios where a virtual ball bounces on a real sidewalk, where real wind moves virtual leaves, where real doors open for virtual objects (see figure 5.1) and where virtual objects get wet when it rains. Furthermore, we wonder, whether virtual and real objects can interact in novel ways, allowing us to experience influences that cannot exist in a purely physical world. Ideally, AR would allow us to both imitate the real world, as well as realize new imaginative realities that go beyond physical laws and allow the virtual and real to behave and interact according to our own ideas.

Of course, the suggested ideas of imitating the real world on the one hand and creating new realities, on the other hand, are not new. The strive for realism as well as the creation of new and imaginative forms of realities can, for instance, be witnessed in the context of literature, gaming, photography and painting. When it comes to computer-generated virtual content, both directions can be traced back to Sutherland's (1965) vision of an 'ultimate display'—a room in which a computer controls the existence of matter. In the paper that describes his vision, Sutherland (1965) suggests: "A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal" (p. 2). With this, he describes computer-controlled objects that interact with the real world just like their real counterparts. At the

Figure 5.1: Real doors can open for virtual objects. Image © Hanna Schraffenberger and Edwin van der Heide.

same time, Sutherland also implies possibilities for realizing different types of behaviors and creating imaginative environments. He emphasizes that such an ultimate display "could literally be the Wonderland into which Alice walked" (p. 2). The idea of moving beyond the simulation of physical laws also comes back in his comments on computer displays in general. In this context, Sutherland (1965) explicitly argues that "[t]here is no reason why the objects displayed by a computer have to follow the ordinary rules of physical reality with which we are familiar" (p.2).

As Sutherland's paper shows, the ideas of mimicking the real world as well as creating new types of realities have a long history. However, augmented reality is no ultimate display, and AR technology cannot control the existence of matter. This raises the question of whether and to what degree both visions can actually be realized in the context of AR. In fact, there are reasons to doubt the feasibility of either idea when it comes to interactions between virtual objects and the real world.

With respect to imitating real-world interactions, one faces the challenge that many virtual objects cannot directly apply forces to real objects (cf. S. Kim et al., 2011). Usually, the real world can affect virtual elements, but virtual objects cannot affect the real world in return. In the context of Sutherlands examples, this means that we can make virtual bullets fly through a real environment, but that these bullets won't have any effect when they hit someone or something real.[1] If the real world does not seem to be affected at all by the behavior and actions of virtual objects, this might seem unbelievable.

[1] Arguably, in the context of bullets this can be considered an advantage rather than a problem.

When it comes to creating new and imaginative forms of actions and reactions, believability is an important issue. It is not clear what interactions and influences between the virtual will be perceived as credible and meaningful. Technologically, there is nothing keeping us from having virtual raindrops 'fall' upwards, from turning virtual frogs into princes when they are kissed, or making virtual objects 'teleport' to an entirely different position when they collide with real elements. A question that arises is whether behaviors that defy physical laws are plausible in a real-world context. As we will see, some researchers seem to believe that for virtual objects to appear as if they were part of the real world, they also have to behave like real objects and stick to the rules of that world. The question arises whether virtual objects might "have to follow the ordinary rules of physical reality" (see Sutherland, 1965, p.2) after all when they appear to exist in the context of our "physical reality". Personally, we do not expect this to be the case and hope to dispute the claim that virtual objects (always) have to behave like physical objects.

In this chapter, we take up these different lines of thought about interaction between the virtual and the real. In particular, we address the following three considerations: First, the virtual is free from physical laws. Hence new forms of influences between virtual content and the real world can be realized. Second, virtual content cannot directly apply forces to real objects. As a consequence, interactions that we know from the physical world might not be possible. Third, not everything that is technically possible is necessarily also credible. For instance, in order to appear as a believable part of the physical environment, virtual objects might have to adhere to the same laws as real objects.

These three considerations inspire us to ask the following questions: What types of interaction between the virtual and the real are both possible and credible? Can the virtual and the real interact like physical objects? Can they interact in new but believable ways? We are interested in both problems that arise when virtual and real objects seemingly exist in the same space, as well as in possibilities that emerge from such an AR setting. In particular, we are interested in new forms of interactions that are unique to AR and that could neither exist in a solely physical nor in an entirely virtual world.

In order to answer the presented questions, we follow both a theoretical and a practical approach. We review existing research and AR works, conduct our own initial series of practical experiments as well as reflect upon these experiments.

The topic of interaction between the virtual and the real has emerged as a central theme in in the previous chapter. Because we want every chapter to be able to stand on its own, we will revisit topics and examples discussed in the previous chapter, and in particular section 4.9 and section 4.10. However, we will move far beyond the previously discussed material and primarily address the topic from new perspectives. For instance, we have made a distinction between physical interaction on the one hand and behavioral interaction on the other hand in chapter 4. In this chapter, we choose a different point of view. We focus on interactions that mimic real-world interactions, as well as explore imaginative forms of interactions, that do not exist in reality, but that nonetheless appear believable. In line with this, we distinguish between (1) *imitative* interactions that could actually occur between physical elements in the real world and (2) *imaginative* interactions that cannot exist in a purely physical world, but that are perceived as credible or convincing nonetheless.

The main goal of this chapter is to answer two key questions: (1) whether virtual objects can interact with physical objects in a realistic manner as well as (2) whether they can interact in imaginative but believable ways. We first search for answers to these questions in existing AR research. This theoretical exploration is presented in section 5.1. Subsequently, we take a more practical approach to interaction between the virtual and the real and address the questions with a series of small exploratory experiments. This practical exploration is presented in section 5.2. Finally, we present a general discussion and conclusion (section 5.3). We reflect on our findings and conclude that virtual and real objects can believably simulate real-world influences as well as influence each other in imaginative ways that have no equivalent in the physical world.

As mentioned, we are particularly interested in imaginative but yet believable forms of interaction between the virtual and the real. In this study, the question whether the interaction is believable was evaluated from the author's subjective point of view. Furthermore, the question was addressed in the context of an 'ordinary everyday environment'. This is important because the believability of an object's behavior likely depends on the situation and context in which the behavior takes place. For instance, different forms of behavior will be accepted as believable in the context of a game than in the context of a working environment. (This is likely true both for real and for virtual objects.)

Our interest in believable forms of *interaction* between the virtual and the real entails an interest in the *behavior* of virtual objects. However, our key interest is virtual behavior in relation to the real world, rather than virtual behavior as such. The more general question of when the behavior of virtual objects is believable falls out of the scope of this thesis. We are focusing on the interaction between the virtual and the real because this issue is specific to the field of AR.

This chapter addresses two issues that are often approached independently from each other in existing AR research: First, the interaction between a participant (user) and virtual content. Second, the interaction between virtual objects and other physical objects in their surroundings. We address both of these topics, but propose a view that consolidates the two: We see the participant as part of the augmented environment. Accordingly, we see interaction between virtual content and the real environment as a broader, more general field that also encompasses the interaction between a participant and the virtual objects.

The idea of interaction between a real environment and virtual content entails that there is some kind of mutual influence between the virtual and the real world. Given our interest in the participant's experience (rather than technological aspects), we are focusing on scenarios where the participant either witnesses interaction between virtual objects and the real environment and/or interacts with virtual objects her/himself. If we look at existing AR projects, participants often interact with virtual content on a technological level: Many AR systems react to the movement of the participant and consequently, present virtual content that depends on the participant's point of view (see subsection 3.1.2).[2] For instance, a virtual cup might look different, depending on whether a participant looks at it from above or from the side. If the participant reacts to what they see, and e.g., move to see an object from yet a different angle, one could speak of a mutual influence (and thus interaction) between the virtual and the real. However, in our opinion, this does not mean that the participant also *experiences* some interaction with the virtual content. Arguably, simply looking at an object from different points of view is not experienced as interacting with the object since the object itself does not react to the actions of the participant. Similarly, the fact that an object looks different from different angles does not make it feel like the object is affected by us. Accordingly, such scenarios fall out of the scope of our exploration. Instead, we focus on scenarios where virtual objects actually appear to be affected by the real world and vice versa. This is, for instance, the case when a virtual object changes its size, color, shape or position as a response to colliding with a real object. In our review of existing AR literature, we will make different views on what constitutes interaction explicit. However, unfortunately, it is not always clear how other authors define interaction.

[2] In fact, AR is often defined in terms of such systems (e.g., Azuma, 1997).

Our exploration is focused on underlying ideas and conceptual possibilities rather than issues of implementation. Yet, we will at times mention different technological approaches that facilitate interactions between the virtual and the real. This is because sometimes, conceptual ideas and technological solutions are closely interlinked. Furthermore, we want to support future research and development that intends to implement the underlying ideas.

Given that we are interested in conceptual rather than technological possibilities, our practical explorations use basic technological implementations. We generally work with cheap and readily available office hardware rather than dedicated AR devices. In our opinion, this is sufficient to experience (basic/fundamental) interactions between the virtual and the real and hence, we see no need to work with different materials instead. So far, this practical exploration is solely based on our own experiences with the AR scenarios. It does not yet include any empirical research with participants. However, it can serve as the first step towards such empirical studies, as it identifies possible forms of interaction and scenarios that could be studied with participants in the future.

In addition to the AR research field, many other disciplines are also interested in interactions between the virtual and the real. For instance, research into conversational agents has been very concerned with creating virtual humans that converse with and react to real human input just like a human (see, e.g., Cassell et al., 2000). In this chapter, we primarily focus on issues that are unique to AR and that arise from the fact that virtual and real objects seemingly exist *in the same physical space*. Topics that are a primary concern in other research areas fall out of the scope of our investigation.

5.1 Theoretical Exploration

The presence of virtual content in an otherwise real environment opens up possibilities for influences between this environment and the virtual content. However, it is still unclear what forms these interactions can take. In order to get a first idea about what reactions and interactions between the virtual and the real are possible and credible, we will have a look at existing AR projects and review opinions on how interaction between the virtual and the real can, should or could look like.

In the following, we will first address imitative interactions and subsequently explore imaginative interactions. However, this clear distinction between the two is somewhat misleading. Rather than as two distinct groups, the two forms of interaction can be seen as a continuum. Often, projects will mimic reality in some form, while deviating from it in other ways. We have placed ideas in one of the two categories based on the concept we want to emphasize and illustrate—this might not always be the most prominent feature of a certain project.

5.1.1 Imitative Interactions

Can virtual objects interact with the real world in the same manner as real objects? According to some researches, realistic interaction between the virtual and the real are not simply a possibility but rather, a *necessity* for successful AR.

For instance, Breen et al. (1996) point out: "For the new reality to be convincing, real and virtual objects must interact realistically" (p. 11). Effects that, according to the authors, need to be considered in AR include occlusions, shadows, reflections, refractions, color bleeding, kinematic constraints, collisions as well as responses to collisions and external forces. The authors not only assert that such real-world effects and influences have to be implemented in AR, but also propose techniques that approach some of the issues. In particular, they present techniques for realizing occlusions between virtual and real objects as well as for placing dynamic virtual objects on top of static real objects. They do this by 'simulating gravity' and detecting collisions between virtual and real objects. Essentially, virtual objects are moved downwards in the real space until they collide with a real object. As a result of this process, virtual objects are placed on real objects. For instance, a virtual lamp might appear to stand on a real desk.

The Physical Artifact

Breen et al. (1996) are not alone with their view that realistic interactions between the virtual and the real are necessary. For instance, S. Kim et al. (2011) write: "In order to make virtual objects move as if they coexisted with real objects, the virtual object should also obey the same physical laws as the real objects, and thus create natural motions while they interact with the real objects." (p. 25).[3] The authors not only argue for such realistic interactions but also identify challenges that arise when attempting to implement them. More specifically, they illustrate that problems can arise due to the inability of virtual objects to affect real objects. They argue that when a virtual and real object collide, both objects should be affected by this collision. However, as AR systems typically only can control the movement of the virtual object, a real object will usually appear unaffected by a collision with a virtual object. The authors believe that such interactions "may contradict the physical cognition of humans" and argue that it "diminishes the sense of realism of AR". S. Kim et al. (2011) coin this phenomenon "physical artifact" and continue to explore when these artifacts occur, demonstrate instances of the problem and also present ideas about how the problem can be avoided.

[3] It is not clear whether the authors believe this to be generally true, or only assume this to be the case when a participant perceives the virtual object as a real object. As we will see later, they give an example where a real paper cup remains unaffected when it is hit by a virtual ball. In this context, they write "If a viewer perceives the virtual ball as a real one, this physically incorrect response will contradict the physical intuition of the viewer, and thus may harm the immersiveness of the viewer considerably" (p. 27). In line with this, it might make a difference whether the virtual object is perceived as a real or as a virtual object.

The practical exploration of these physical artifacts by S. Kim et al. (2011) includes several interesting examples of influences between virtual objects and the real world. For instance, they present an example where virtual boxes and spheres fall down, collide with a real table tennis racket and, according to the authors, show plausible responses. Furthermore, they demonstrate an example of the "physical artifact". A virtual ball falls down, bounces off a physical slanted plane, and collides with a real paper cup. This collision causes the virtual ball to move into a different direction. However, the real cup remains unaffected. From a technological point of view, this is not surprising, as the virtual ball does not actually apply any force to the cup. However, from a perceptual perspective, things might appear differently. As the authors explain "[i]f a viewer perceives the virtual ball as a real one, this physically incorrect response will contradict the physical intuition of the viewer, and thus may harm the immersiveness of the viewer considerably" (p. 27).

The authors also propose a solution to avoid such collisions. Their idea is to change the parameters used in the physical simulation in a way that maintains the realism and at the same time, avoids the collision. They demonstrate this by adapting the previous example. Due to a small adjustment in one parameter, the virtual ball bounces off the real plane in a slightly different (but still credible) angle, thereby avoiding the collision with the cup.

Imitating Optical Interactions

In line with the belief that realistic interactions are necessary, we can find a wide variety of projects that attempt to realize such realistic interactions (cf. section 4.9). With respect to this, a lot of research seems to focus on realizing realistic *optical effects* between virtual objects and the real world. To mention just a few examples: Many researchers work on methods that allow an AR system to take the illumination of the real world into account when rendering virtual objects (e.g., Madsen et al. (2006) and Kanbara and Yokoya (2004)). This makes it possible for real light sources to affect the appearance (e.g., shading) of virtual objects. Furthermore, the information about the illumination of the real world can be used to make virtual objects cast realistic shadows onto the real world and affect the appearance of the real world in return. In addition, AR research focuses on realistic caustics, reflections and refractions. For instance, Kán and Kaufmann (2012) demonstrate a rendering system that is capable of these optical effects. Their demonstration displays a virtual glass that casts a virtual shadow onto the real world as well as features correct refractions of surrounding elements, such as a person's hand and physical colored cubes that stand next to the virtual glass (see figure 4.9). Similarly, Pessoa et al. (2010) propose a rendering technique that focuses on the effects of the real environment on the appearance of virtual objects. Their demonstrations include, for instance, a virtual vase that appears to be illuminated by the real environment, a teapot reflecting surrounding physical objects as well as color bleeding effects where light from real surfaces appears to color virtual objects.

While visual effects get a lot of attention, very little research addresses similar issues with respect to other modalities. One of the few exceptions is the work by Lindeman and Noma (2007). The authors point out:

> In order to attain a truly merged experience, the two [real-world and computer-generated] stimuli should undergo similar transformations, so that, for example, a virtual character receives the same lighting effects (light position and intensity) as objects in the real world. In fact, this applies to all sensory modalities; the voice of a virtual character should also be influenced by environmental objects, such as occluders or reflectors. (p. 175).

Imitating Dynamic Interactions: The Real Affects the Virtual

In addition to research that focuses on realistic optical interactions, research has also pursued realistic *dynamic* influences and interactions. Here, the main focus is on making virtual objects move as if they were indeed affected by the real world. This often happens with respect to gravity. Often, virtual objects appear to have a physical mass and seemingly are affected by gravitational forces. This happens, for instance, in the above-discussed exploration of the physical artifact by S. Kim et al. (2011). As illustrated, it is difficult for virtual objects to physically affect real objects. However, real objects can easily affect virtual objects. In the exploration by S. Kim et al. (2011), a physical slanted plane and a real paper cup affect the trajectory and movement of the virtual ball. Similar examples have been presented by Chae and Ko (2008), who simulate gravity, and take attributes such as weight, gravity, friction, elasticity and force into account when determining the movement of virtual objects. They demonstrate this with a virtual ball that falls downwards, collides with a real object, and bounces off this object. Another similar example of a virtual ball that bounces on a real table is provided Valentini and Pezzuti (2010).

The idea of simulating real-world interactions between real and virtual objects often comes back in the context of AR games. For instance, in the AR version of Air Hockey by Ohshima et al. (1998), hitting a virtual puck with a real mallet, causes the puck to change direction—presumably in the same way as a real puck. Furthermore, Namee et al. (2010) propose an engine for creating plausible physical interactions between virtual and real objects in the context of AR games. To demonstrate this engine, the authors present two proof-of-concept AR games. The first is a table-top racing game where virtual cars interact with both virtual and real objects. For instance, they can crash into a real object or drive over a real ramp. In their second game, the player has to move virtual crates around the environment with a small real robotic forklift. The real forklift can, e.g., raise and lower crates with its fork, push around and carry crates or crash through multiple crates. All of these interactions have an equivalent in a solely physical world.

As discussed above, simulations of dynamic real-world interactions are often incomplete due to the fact that many virtual objects cannot affect the real world. Essentially most projects only simulate the influence of the real world on the virtual objects. For instance, to the best of our knowledge, the collision between the virtual puck and the real mallet in "AR²Hockey" (Ohshima et al., 1998) only affects the puck and has no effect on the physical mallet at all.

Imitating Dynamic Interactions: The Virtual Affects the Real

Whereas many projects explore how the real world can affect virtual objects, rather few projects focus on the way virtual objects can affect the real world. One of the few exceptions is the project called *Kobito - Virtual Brownies-* by Aoki et al. (2005). Here, virtual creatures (so-called Kobitos) move a real tea caddy. A similar project has later on been realized by Kang and Woo (2011). In their project, a virtual character is able to interact with a physical toy cart. For instance, it can push and pull the cart. Furthermore, participants can interact with the virtual object through interaction with the physical object. E,g., they can move the cart, which can cause the virtual character to fall down. Both projects extend real objects with electronics (e.g., motors) to allow the virtual characters to move the real objects.

A different approach to allowing virtual objects to affect real objects is found in the table-top game called *IncreTable* by Leitner et al. (2008). In this game, both virtual and real items can be arranged on the table to solve puzzles. Among the available objects are, e.g., virtual and real domino stones. In order to facilitate interaction between the virtual and real dominos, the authors implemented so-called portals (see figure 5.2). These special physical interfaces can both push a real domino stone when it is hit by a virtual one as well as detect a falling real domino stone to push a virtual one.

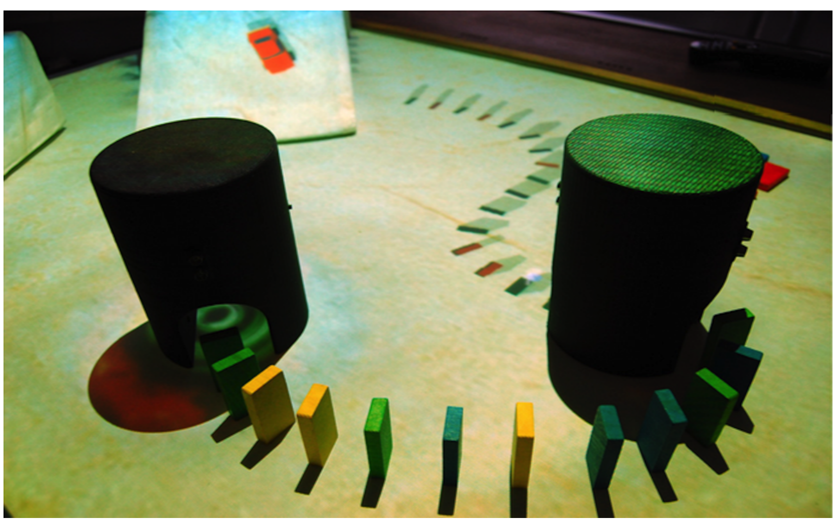

Figure 5.2: Virtual and real domino stones can interact with the use of so-called portals. Reprinted from J. Leitner et al. (2008). "IncreTable, a mixed reality tabletop game experience". In: *Proceedings of the 2008 International Conference on Advances in Computer Entertainment Technology*. ACM, pp. 9–16. Reprinted under fair use.

Another project where the virtual affects the real is the artwork "Beyond Pages" by Masaki Fujihata (see Kunst und Medientechnologie Karlsruhe, n.d.; MediaArtTube, 2008). The work consists of a real room, that contains, a real desk, chair and lamp. On the desk, there is a virtual book and stylus that allows the visitor to interact with the virtual book. On one of the pages, a virtual light switch is depicted.

If the visitor switches the virtual switch, the real lamp in the room can be turned on/off. Here, a physical interface from the real world is replaced with a virtual interface.

As these projects show, the virtual can have an effect on the real world. This effect can be *simulated*, as in the case where virtual objects cast virtual shadows onto real objects (see, e.g., figure 4.9). However, the outcome of the interaction can also be real. For instance, the above-discussed virtual tea caddy and toy cart *actually* move in the real world and the real domino stones *actually* fall when 'hit' by virtual dominos.

Utilizing Real-World Interactions

Another approach to interactions between the virtual and the real is not to mimic them, but to make use of actual interactions in the physical domain. A simple example of this concept would be playing back the voice of a virtual character via speakers. If this happens, the characteristics of the surroundings will naturally affect the voice. For instance, if the sound of a virtual creature is played back on a speaker in a big church, it will sound different than if it is played back outside without any need to simulate this effect. We hence can utilize natural interactions that occur in the physical domain.

An example of a project that makes use of interactions that naturally occur in the physical domain is the installation *Radioscape* by Edwin van der Heide (2000-). The installation consists of several radio transmitters that are distributed over a part of a city. Each transmitter broadcasts one layer of a meta-composition. Listeners can pick up several signals at a time with a custom developed receiver. The volume of each of the single layers depends on the listeners' distances from the corresponding transmitters. Due to the chosen wavelength, buildings become conductors and resonators for the transmitted signals. The physical environment is excited by and responds to the transmitted radio waves, ultimately affecting the virtual content and influencing what one hears. Although this interaction happens in the physical domain, we can argue that the transmitted virtual content interacts with the physical landscape.

A completely different approach that also utilizes real-world interactions is found in the commercial product *Sphero* (2011). Sphero is a robot ball that—when viewed with the corresponding smartphone app—is turned into a virtual beaver (cf. J. Carroll and Polo, 2013). Because the virtual ball is affected by the real world (it can, e.g., not pass through real walls, and is affected by gravity) the virtual beaver is also affected by the real world accordingly.

Participant-Focused Interaction

The idea of mimicking real-world interactions also comes back in the specific case where a *participant* interacts with virtual content. For instance, Craig (2013) claims that AR not only allows us to interact with virtual content but also, that we can interact with it *in the same way* as we interact with physical objects:

> In brief, the core essence of an augmented reality experience is that you, the participant, engage in an activity in the same physical world that you engage with whether augmented reality is involved or not, but augmented reality adds digital information to the world that you can interact with in the same manner that you interact with the physical world. (p. 2)

It has to be noted, though, that Craig's definition of interaction is rather broad, and appears to include looking at virtual content from different perspectives. For instance, he writes:

> [...] a person can sense the [digital] information and make changes to that information if desired. The level of interactivity can range from simply changing the physical perspective (e.g., seeing it from a different point of view) to manipulating and even creating new information. (p. 16)

Furthermore, Craig (2013) also points out the possibility to interact with virtual content in new and additional ways that have no equivalent in a physical world. For instance, unlike a real house, a virtual house in a vacant lot could be moved around or viewed in different colors. (Interactions that are impossible in a physical world will be discussed in subsection 5.2.2.)

An example that shows that real-world interactions can indeed be imitated, is the above-mentioned AR version of AIR hockey "AR²Hockey" by Ohshima et al. (1998). Here, two players play air hockey using a real mallet to hit the virtual puck that moves over a real table (cf. Azuma et al., 2001). This means, that the game simulates the interaction between a puck and mallet that we know from the real world. Similar ideas have been used in other contexts. For instance, the AR version of the game Quake (Piekarski and Thomas, 2002) allows participants to virtually shoot at monsters by means of a physical toy gun—essentially also copying an interaction that we find in the real world.

Another project that allows a participant to interact with virtual content in the same way we interact with real content has been realized by Corbett-Davies, Dünser, and Clark (2012) and Corbett-Davies, Dünser, Green, et al. (2013). In contrast to the above-mentioned projects, it does not make use of a physical interface but allows participants to interact with virtual spiders with their bare hands. Participants can, for instance, pick spiders up and carry them around.[4]

The idea that AR can allow for similar interactions as the real world is also taken up by Bau and Poupyrev (2012). Similar to Craig (2013), the authors state that "[t]he fundamental premise of AR is to enable us to interact with virtual objects immediately and directly, seeing, feeling and manipulating them just as we do with physical objects." (p. 89:1).

[4] The underlying idea that people with a fear of spiders can interact with these virtual spiders, while they could never interact with real spiders in the same way, suggests that interaction with virtual objects in some way differs from interacting with actual spiders even when it is extremely realistic. Presumably, the fact of knowing that something is virtual will change how the interaction is experienced, and thus creates some difference.

However, Bau and Poupyrev (2012) emphasize that this goal is often *not* reached and consequently propose a means to change this. Their tactile technology REVEL provides virtual tactile feedback that can extend real, physical objects by means of virtual textures that are felt when touching the object. Ultimately, such a tactile augmentation of real objects leads to an object with both a virtual and a real component that a user can not only see but also touch and interact with physically.

Like Bau and Poupyrev (2012), several other researchers emphasize common limitations when it comes to interacting with virtual objects in AR, and consequently, propose a way to change things. For instance, Vallino and C. Brown (1999), point out that "Augmented reality systems have been interactive only to the extent that the user could move about the workspace and be a passive viewer of the visually augmented scene" (p. 199).[5] To change this, the authors then propose a setup that allows users to physically interact with virtual content by means of a Phantom force-feedback device. As discussed in subsection 4.4.5, this device has similarities with a small robot arm (cf. Vallino and C. Brown, 1999) with a thimble at the end. Placing their finger in the device's thimble, the participant can feel the surface of a virtual object, experience its weight and dynamic forces, as well as move the object around within the real environment. In their demonstration, participants can, e.g., experience a virtual globe, spin it around its axis, feel the difference between water and land, or move the virtual cube around in real space with their finger.

Billinghurst (2001)[6] also critiques the then existing possibilities of interacting with virtual content in AR. Similar to (Vallino and C. Brown, 1999), he asserts that "*interaction* with AR environments has been usually limited to either passive viewing or simple browsing of virtual information registered to the real world. Few systems provide tools that let the user interact, request or modify this information effectively and in real time" (Billinghurst, 2001, p. 1, emphasis in original). He consequently introduces the concept of "tangible AR interfaces" as a means to change this. Tangible interfaces take the form of physical objects that have virtual objects linked (registered) to them. Consequently, a user can interact with virtual objects by manipulating the corresponding physical object. The resulting interactions can both mimic real-world interactions, as well as take novel imaginative forms. Both happens, e.g., in the SharedSpace Siggraph 99 project. Here, physical game cards with AR markers (see subsection 3.1.2 for information on markers) on them provide a physical counterpart to the virtual content that is associated with them. The cards can be picked up and moved around to view the attached virtual objects from different perspectives. Furthermore, participants can place corresponding virtual cards together, causing interactions between the virtual objects. These ideas are particularly interesting to us because the implemented interactions only partially

[5] In our opinion, only being able to passively view virtual content implies that these environments provided *no* possibilities for interaction with this content. However, the idea of viewing virtual content from different perspectives is often seen as a form of interaction with the content. This could be because the virtual content indeed adapts to and reacts to the participants movement on a technological level. Here, we approach the topic from a perceptual perspective. Hence, an object that appears static and that does not seem to react to one's movement is not considered interactive because it does not appear to be interactive.

[6] and later Billinghurst, Kato, and Poupyrev (2008) as well as Billinghurst, Grasset, et al. (2009)

mimic real-world interactions and also introduce what the authors refer to as “table magic”. For instance, if a physical card is tilted, the virtual object is supposed to slide across the card surface, which mimics physical real-world interactions. However, if a card is shaken, a virtual object can appear on the card or the object can change into another object—naturally, this is something which could not happen in a purely physical world. Kato et al. (2000) put it like this:

> Some of these commands simulate physical phenomena in the real world and other simulate table magic. In all these cases we establish a cause-and-effect relationship between physical manipulation of the tangible interface object and the behavior of the virtual images. (p. 118)

In the following section, we will address such interactions that take imaginative forms rather than mimic our physical reality.

5.1.2 Imaginative Interactions

Virtual objects do not have to adhere to physical laws. Hence, they can behave differently and potentially, also interact with and react to the real world in new and imaginative ways. Unfortunately alternative forms of interaction have gained very little attention in the context of AR so far. In the following, we will review research and practical projects that show that believable imaginative interactions might be possible. Unlike the projects in the previous section, the reviewed examples generally focus on interaction between a participant and virtual content. This is the case because existing research has paid little attention to imaginative interactions between virtual content and the real environment in general.

One of the few examples that build on new forms of interaction are those AR projects that facilitate some form of x-ray vision and that allow participants to have a look inside or see through physical objects. An example is the system by Bajura, Fuchs, et al. (1992), which visualizes ultrasound echography data within the womb of a pregnant woman and thus, let’s a doctor see through parts of her physical body. Next to the medical domain, this concept is also common in outdoor mobile augmented reality applications. For instance, the mobile AR tools by Bane and Hollerer (2004) make it possible to view the area behind physical walls. As noted by Kalkofen et al. (2009), such projects that make it possible to see hidden or occluded objects seemingly go beyond the physical laws of light propagation. In our opinion, such projects can be seen as a counterpart to projects that simulate realistic optical effects and in particular, realistic occlusions between virtual and real objects.

Another approach where optical effects in AR defy the laws of our physical world is the use of magic mirror setups. The underlying idea is that the real environment includes a mirror that presents a mirrored and augmented version of real world to the participant. Magic mirrors defy physical laws in the sense that a mirror reflects something that is not actually in front of it. Typically, the magic mirror takes the form of some kind of digital screen, such as a computer monitor. For instance, M. Kim and Cheeyong (2015) have proposed such a system in the fashion context. Here the idea is that users can see themselves in the mirror with different outfits, make-up, and hair styles. Another example comes from the artist Sobecka, who has created a magic mirror that allows viewers to see themselves in a new way: An animal head appears on top of their own head and mimics their movement and expressions (see figure 5.3). In addition to mimicking the viewer, the animal occasionally creates its own expressions. The artist reports that viewers feel compelled to follow along and enact these animal movements.

In our opinion, the interaction between magic mirrors and the real world has both imaginative and imitative qualities. On the one hand, magic mirrors act like real mirrors and present what is in front of them. In this sense, they can be considered to imitate real-world interactions. On the other hand, the name "magic mirror" suggests that there is something mysterious or supernatural going on. If the magic mirror is experienced as something magical rather than natural (e.g., because it reflects things that are not really there), they can be considered "imaginative".

Figure 5.3: In Sobecka's mirror, the viewer sees an animal overlaid on their own reflection. Image from http://www.gravitytrap.com/artwork/perfect-creatures. Printed under fair use.

Although few projects focus on imaginative interactions between the virtual content and real objects, there are some projects that allow a participant to interact with virtual objects in new ways using physical objects. An example is the above-mentioned Siggraph 99 project (Kato et al., 2000). In this context, we have already seen that shaking a physical card can cause a virtual character to appear or to change into another character. Similar interaction possibilities have been explored with the so-called *MagicCup* interface (Billinghurst, Kato, and Myojin, 2009). This tangible interface allows participants to cover virtual objects with the cup. The MagicCup then "holds" the virtual object and can be used to interact with it. Interaction using the cup often mimics physical interactions (e.g., one can move a virtual object around by moving the cup). However, the MagicCup also allows for a form of interaction that defies physical laws: by shaking the cup, the object inside is deleted. A similar concept has been explored with the so-called "Magic paddle" (Kawashima et al., 2001). Here, participants use a small real paddle to interact with virtual furniture. Like with the Siggraph 99 project (Kato et al., 2000) and the *MagicCup* (Billinghurst, Kato, and Myojin, 2009), some interactions mimic real-world interactions whereas others could never exist in a purely physical world. For instance, virtual models can be removed from the space by hitting them with the paddle.

Aside from using simple physical objects, participants can also interact with virtual content using some sort of digital or virtual interface. This form of interaction is, e.g., part of the mobile game *GeoBoids*, which will be explained in more detail below. The game allows players to catch virtual bird-like creatures by making a swiping gesture on their phone's touch-screen.

In addition to using physical objects, digital interfaces and virtual controls, some AR projects furthermore allow the users or participants to affect the virtual by means of hand gestures. Such gestures can mimic the movements one would make to affect an actual physical object, but they can also allow for new and additional forms of interactions that are not possible in the real world. Such ideas are, for instance, realized in the work by Hürst and Van Wezel (2013). They allow users to interact with virtual objects that appear in the real world when the scene is viewed through a mobile's screen. In addition to viewing the objects, users can, for instance, scale small virtual objects up and down by approaching the object and then increasing and decreasing the distance between two fingers. On the one hand, such interactions would be impossible with most physical objects, and in this sense, can be considered to suspend physical laws. On the other hand, we would likely make a similar gesture to transform a real rubber band. Also, we are quite used to making similar gestures to scale digital documents on the screens of touch-screen devices. In this sense, the interaction can be considered to mimic interactions we know well from the digital domain rather than from the physical world.

Another yet different form of 'imaginative interaction' is part of the iOS application *Konstruct* (see Alliban, n.d.). Here, real sounds create virtual objects in the space. The resulting three-dimensional sculptures can be viewed in the real environment through the screen of a mobile device. In the case of the Konstruct app, the underlying idea is that a user produces these sounds themselves, for instance, by speaking whistling into the microphone. However, the same mechanism of sound seemingly creating matter can of course also be triggered by any other sound in the environment.

It often is difficult to say whether interactive behavior mimics the real world, or takes a new imaginative form. This is especially difficult when it comes to behavioral interactions, that not necessarily contradict any laws of nature. A form of interaction that, in our opinion, falls somewhere in the area in between imaginative and imitative is part of the mobile AR game *GeoBoid* by Lindeman, G. Lee, et al. (2012). In their game, players are surrounded by flocks of virtual geometric creatures called GeoBoids. These creatures are represented both visually as well as by means of spatialized audio using the player's phone. As mentioned before, players can catch the birds by making a swiping gesture on the phone's touch-screen. However, in addition, the game also allows for sound-based interaction with the birds. Players can scare the flock by whistling at a certain pitch and for a certain duration. Whereas the idea of scaring animals by means of sound is certainly something we know from the real world, the idea that a certain pitch has to be held for a certain amount of time is still quite different from how we scare real animals.

Finally, the popular game *Pokémon Go* gives us another reason to believe that imaginative interactions can be believable. In this game, players can catch Pokémon by throwing so-called Poké Balls at them. When a ball hits the creature, the creature "magically" appears to be captured inside of it (some argue their matter is transformed into pure energy). Although these interactions take place between two virtual objects, we can easily imagine similar scenarios where one of the two objects (e.g., the ball) would be a physical object.

As these examples show, interactions between the virtual and the real can differ quite a lot from the interactions we encounter in a purely physical world. This can be explained by the fact that virtual objects do not have to follow physical laws. As a consequence, they can, for instance, appear out of nothing, change their size, color, shape, teleport, or disappear entirely. If such actions are linked to actions of a real participant or physical object, this facilitates new forms of interaction that have no equivalent in a physical world.

5.1.3 Preliminary Insights

Our theoretical exploration provides us with preliminary answers to our key questions: Both imitative and imaginative interactions between the virtual and the real in AR are possible. However, judging from largely technology-focused descriptions, it is difficult to tell whether or to what degree they are also experienced as believable.

With respect to imitating real-world influences and interactions, much work focuses on creating realistic optical effects, such as shadows and reflections. Furthermore, some work addresses realistic collisions and other dynamic influences between virtual and real objects. For instance, several projects show that basic real-world interactions, such as a virtual ball that bounces on a physical object, can be simulated (e.g., Chae and Ko, 2008; S. Kim et al., 2011; Valentini and Pezzuti, 2010). Interactions between participants and virtual content also often mimic interactions that we know from the real world. This is, for instance, the case when we push a virtual puck with a real mallet when playing Airhockey (Ohshima et al., 1998), when we fire a virtual bullet by pulling the trigger on a physical (toy) gun (Piekarski and Thomas, 2002) or when we carry a virtual spider on our hand (Corbett-Davies, Dünser, Green, et al., 2013).

A main concern when it comes to imitating real-world influences is to make real objects react to virtual objects. Paradoxically, making virtual objects react to the real environment in a realistic manner can cause real objects to seemingly behave unrealistically (see S. Kim et al., 2011). If, e.g., a virtual ball hits a real bowling pin and changes its course, the real bowling pin might seem to behave weirdly if it is not affected by the collision at all. A key question is thus how virtual objects can affect the real world.

We have encountered a few projects that address this challenge and where virtual elements actually affect real objects. For instance, some projects extend real objects with electronics to make them 'movable' by virtual characters (Aoki et al., 2005; Kang and Woo, 2011). Furthermore, we have seen interfaces that allow virtual domino stones to knock over real stones (Leitner et al., 2008). These forms of interaction are interesting because here, virtual objects cause a real, physical change in the world.

In addition to projects where virtual objects *actually* affect the real world, we have also encountered various scenarios where virtual objects only *seemingly* affect the real world. This is, for instance, the case when a virtual object appears to cast a shadow onto the real world, while in reality, the real world remains unaffected.

When it comes to realizing new forms of influences and interactions, most existing projects concern interactions between a participant and virtual content. For instance, we have encountered projects where users can make sounds to create virtual visual 3D sculptures (Alliban, n.d.), where participants can make virtual objects disappear by shaking a corresponding physical object (Billinghurst, Kato, and Myojin, 2009) and where users can resize virtual objects by making gestures with their fingers (Hürst and Van Wezel, 2013). In addition, we have seen projects that allow participants to interact with virtual elements using digital touch-screens (Lindeman, G. Lee, et al., 2012), or virtual controls (Schmalstieg et al., 2002). These projects build on interactions we know from the digital domain, rather than from the physical world. In their entirety, these projects illustrate that various forms of interaction that differ from how we interact with physical objects are possible. However, the question of whether these interactions also are believable has received little explicit attention so far.

We have encountered examples that focus on interactions between the real world and virtual content as well as examples that specifically focus on the interaction between a participant and virtual content. As many projects show, the two are closely intertwined. For instance, both the car racing game as well as the forklifting game by Namee et al. (2010) involve a participant that interacts with a real object that, in turn, interacts with virtual objects in the environment. Likewise, the artwork *Beyond Pages* involves interaction between a virtual light switch and a real lamp, but also a participant who interacts with the virtual switch. Furthermore, interactions between virtual and real objects can facilitate interaction between a participant and virtual content. We have seen this, e.g., in the project by Kang and Woo (2011), where one can play with a virtual character that pushes or pulls a little toy cart by interaction with the cart. We hence believe it makes sense to consider the participant, the virtual content and the physical aspects of the environment as an integrated whole.[7]

[7] A question that arises in this context is whether the interaction between a participant and something real constitutes AR if there is no real environment. In line with our definition in chapter 3, we see the real environment as an important element of an AR experience.

Our theoretical exploration also reveals some gaps in existing research. Little work seems to incorporate imaginative influences between virtual and real objects. Another area that has received almost no attention so far are non-visual or multimodal aspects of interaction between the virtual and the real. We believe it is important to consider all senses because we also foresee some non-visual responses when virtual and real objects interact. For instance, we might expect to hear sounds if virtual raindrops hit the window.

As we have seen, some researchers consider interaction between the virtual and the real not simply a *possibility* but rather a *necessity*. We, too, believe that for virtual and real objects to appear as if they existed in the same space, they should be able to affect each other. For instance, we would expect a real window to break when it is hit by a virtual ball and expect a virtual creature to get wet when it rains. However, in contrast with some existing views, we are not convinced that such interactions always have to mimic real-world interactions—rather we are inspired to explore other possibilities as well.

Although our review has provided us with preliminary answers, many questions remain. In particular, little work has addressed the issue of how virtual objects can affect the real world when imitating physical interactions. Furthermore, few imaginative interactions between virtual content and the real world have been realized. We will address both topics as part of our practical exploration.

5.2 *Practical Exploration*

In order to explore if and how the virtual and real can interact, we conduct a small series of experiments. We divide this exploration into two main categories: (1) Imitative interactions, which focuses on simulating real-world interactions and (2) Imaginative Interactions, which focuses on influences that have no equivalent in a solely physical world but ideally, are believable nonetheless. In both of the two categories, we present three explorations.

As mentioned, the discussion of the practical exploration is solely based on our own experiences with the different scenarios and does not include any empirical research with participants.

Setup

Unless specified otherwise, our setup used for the exploration is based on relatively cheap conventional office equipment rather than dedicated AR technology. On the hardware side, our setup consists of a monitor, a computer, loudspeakers, and a webcam that provides a live-view of the environment. On the software side, the project uses self-written Max/MSP/Jitter software (see https://cycling74.com/products/max/), which makes use of Max's built-in physics engine. The software is used to integrate virtual objects into the view of the real environment. As a result, participants can see virtual objects in the real on-screen environment on the monitor as well as potentially hear virtual objects via the speakers. Unlike typical AR setups, the setup is fixed, and only shows the augmented environment form one static point of view, namely the fixed position of the webcam. Whereas many existing AR projects are interested in exploring the technological possibilities, we want to explore the *conceptual* possibilities. For this goal, this simple setup is sufficient.

5.2.1 Imitative Interactions

The first experiments explore whether and to what degree virtual and real objects can (appear to) physically interact like real objects.

Exploration 1: Bouncing Ball

Our first simulation recreates an arguably simple real-world interaction between two objects: a ball that bounces on a surface. As mentioned, similar experiments have been conducted by Valentini and Pezzuti (2010), S. Kim et al. (2011) and Chae and Ko (2008). We hope to validate that this type of interaction indeed is possible as well as believable.

In order for the ball to react to its real surroundings, we have created a virtual reconstruction of the environment in our self-written software and aligned it with the real scenery. (This means that the real desk has a virtual desk as a counterpart. The virtual desk is invisible, but it is positioned at the exact location of the real desk.) Furthermore, we have assigned virtual physical properties such as mass and restitution to the virtual elements and applied gravitational forces (using the Max/MSP/Jitter physics engine).

When we start the simulation and view the environment through the screen, a virtual ball appears to bounce on the desk in front of us (see figure 5.4). On first sight, the experiment appears to be a success:

it is possible to simulate certain existing real-world interactions in AR. However, on second thoughts, it becomes clear that the virtual ball does not have any effect upon the real table. If a real ball hits a table, the collision also goes hand in hand with a distinct sound. However, the simulation remains silent. The example only shows that the real can influence the virtual and leaves us wondering whether and how the virtual can influence the real as well.

In order to overcome this limitation, we adapt the experiment and extend the physical desk with virtual sounds. For this, we use recorded sound samples of a real ball that hits the desk. These samples are consequently triggered when the virtual ball and the virtual representation of the table collide. Every time the ball hits the table, one of several recorded sounds is randomly chosen and played back. We furthermore use the magnitude of the collision to calculate the volume of the playback.

Unfortunately, we have to admit that the result is not convincing (to us) yet. Maybe, because the result is almost but not entirely realistic, we are irritated by the fact that something 'is a bit off'.[8] In our experience, the condition with no sound was more believable than a sound that is not exactly what one would expect.

[8] Similar experiences have been described with respect to almost but not entirely human-like robots and in the context of the so-called uncanny valley effect (e.g., Seyama and Nagayama, 2007). However, as this effect is associated with human-likeness, it would be rather surprising to find something similar when it comes to simple physical objects.

Of course, the fact that we are not able to create a realistic sound response does not show that this is impossible. If anything, we still expect this can be achieved by more carefully considering what sounds would match the visual impression.

Irrespective of the unconvincing result, the example shows that sometimes, we need to extend real objects (the table) by means of non-visual virtual content (the sound samples) in order to simulate reality. This is not surprising: reality is not just something we see. Consequently, we cannot simulate it realistically while only considering visual aspects.

With respect to real-world applications, it would be desirable to not require pre-recorded sounds. A solution that could be explored in the future is using physical modeling of sound (Cook, 2002) to extend physical objects with virtual sounds.

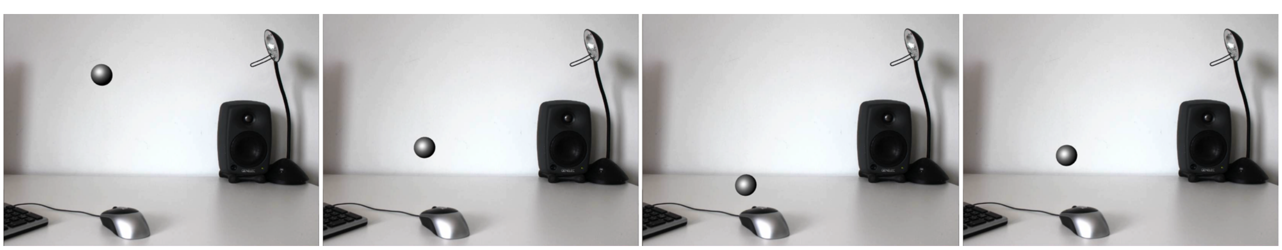

Figure 5.4: A virtual ball is bouncing on a real table. Four snapshots from the live-view. Image © Hanna Schraffenberger and Edwin van der Heide.

Exploration 2: Falling Dominoes

As a next step, we deliberately chose a scenario that seems bound to fail. In this experiment, a virtual ball collides with a row of real dominoes (see figure 5.5). Like in the previous example, the desk has a virtual counterpart, which allows the virtual ball to roll over its surface. Likewise, there is a virtual representation of the first domino stone.

Initially, the screen shows the virtual ball heading towards the real dominoes. Just like in the previous example, the virtual ball reacts to the real: the moment it hits the first stone, the ball changes its direction and rolls back. However, unlike in the real world, the stones do not fall.

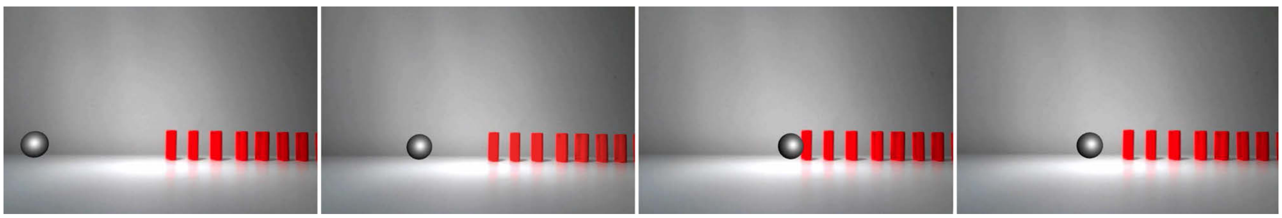

Figure 5.5: A virtual ball approaches a row of dominoes (frame 1 and 2), hits the first stone (frame 3) and consequently changes its course (frame 4). Unlike in the real world, the stones do not fall. Image © Hanna Schraffenberger and Edwin van der Heide.

Based on our own impression, this behavior contradicts our expectations and is not believable at all. Neither the behavior of the virtual nor the behavior of the real elements appears to be credible. We seem to expect a realistic response and want to see the stones falling. Clearly, problems can arise due to the fact that the virtual cannot directly affect the real. As mentioned, this problem has been identified earlier by S. Kim et al. (2011) who call this the 'physical artifact'.

We hope to overcome this limitation by making the virtual object affect the real world. As we have seen in our review of existing work, there are several possible ways in which the virtual can affect the real. For instance, we have seen the use of physical portals that can enable interactions between virtual and real dominoes (Leitner et al., 2008). However, we have another idea: we introduce a physical counterpart that extends the virtual object.

Just like a virtual desk has been acting as a virtual counterpart for the real desk in previous examples, this time, a real ball acts as the physical counterpart for the virtual ball. This is realized by analyzing the camera-image and replacing the real ball with a virtual one. As a result, while looking at the scenery directly, one sees a physical ball. The screen, however, shows a virtual ball instead.

In our own experience, this approach is interesting on three levels. First of all, the setup allows the participant (and in this case, author) to tangibly, intuitively and naturally interact with the object, and roll it towards the dominoes.

Secondly, the result simply looks fascinating: when the virtual ball hits the first domino stone, the stones start falling (see figure 5.6). Although we expect the stones to fall on some level (see exploration 2), we also expect them not to fall on another level. After all, a virtual ball can typically not apply real forces to physical objects. Based on our own experience, we believe part of the fascination is based on the fact that we can see that the ball is not real and yet, affects the real world. We assume that things would look less intriguing, had we created a virtual ball that looks so real that it can be mistaken for a real ball.[9]

[9] From a technological perspective, this example is "nothing new". Like many AR applications, a virtual object (here, a virtual ball) is superimposed onto a camera feed and spatially aligned with a real object (here, another ball). However, on an experience level the result is quite fascinating—likely because we are not used to seeing virtual objects physically affect the real world.

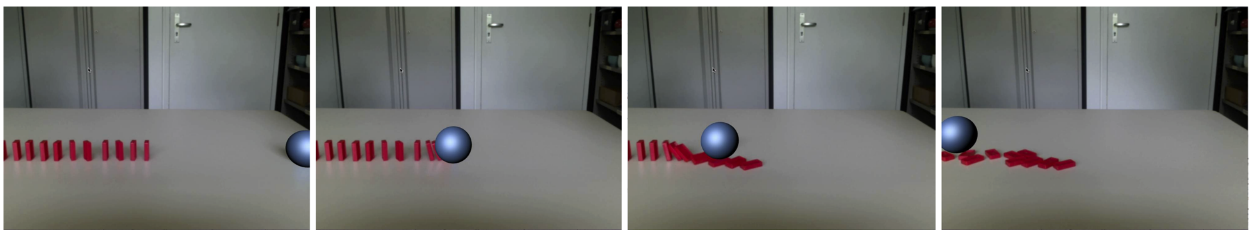

Figure 5.6: A virtual ball approaches a row of dominoes (frame 1) and hits the first stone (frame 2). This causes all domino stones to fall (frame 3 and 4). Image © Hanna Schraffenberger and Edwin van der Heide.

Third, the quality of the execution in terms of visual and spatial realism is rather low—yet we experience a strong sense that the virtual object is present in the real environment. The virtual ball looks a bit too big and, at times, appears at somewhat weird positions in the image (in front rather than behind of the real stones). In our experience, we get a strong sense that the ball is present in the real environment even though it sometimes does not look like it if we analyze the scene visually. In our experience, the interaction between the virtual and the real is such a strong perceptual cue that the virtual object is part of the environment and the contradicting visual information does not seem to matter much.

What makes this approach particularly worthwhile is that the virtual ball can potentially also display behavior that purely physical ball cannot exhibit. For instance, it can change its texture according to its speed, or change its color when it hits a real object. What is more, we can also replace the real ball with any other virtual object and thereby give it qualities that the real object does not have. This approach is found in the earlier mentioned product *Sphero* (2011). Here, a robot ball that is turned into a virtual beaver when it is viewed with a dedicated smartphone app (cf. J. Carroll and Polo, 2013).

Of course, the idea of extending a virtual sphere with a real sphere and the idea of extending a real ball with a virtual sphere are interchangeable. To make this point explicit, we have also applied this concept to a Newton's cradle (see figure 5.7. In our setup, one of the cradle's real spheres is augmented with a virtual counterpart. As a result, it looks like a virtual ball in the resulting digital view of the environment.

Judging from our own experience, watching this Newton's cradle

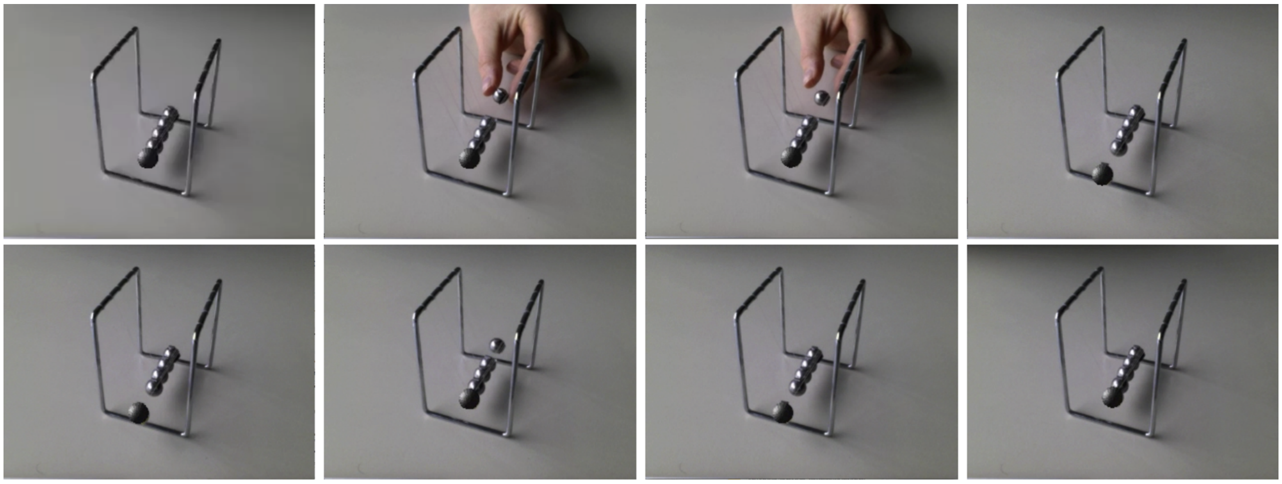

Figure 5.7: One of the physical spheres in a Newton's cradle is overlaid with a virtual sphere. The setup results in a realistic interaction between the spheres and allows for participant interaction with all spheres. Image © Hanna Schraffenberger and Edwin van der Heide.

swing is quite irresistible, maybe because seeing a virtual ball physically interact with the real balls contradict our expectations ("a virtual ball cannot push a real ball") in a pleasant way. Like in the case of the domino stones, we believe the interaction is even more fascinating because we are aware that one of the spheres is virtual. Also here, we expect the resulting image to be much less interesting in cases where the virtual ball is mistaken for a real ball.

Exploration 3: A Door That Opens for Virtual Objects

With this last exploration, we move from physical-like forces to behavioral interactions (section 4.10). The underlying idea is that real objects in the environment can sense and react to the behavior of virtual objects. We explore this idea in the context of a real automatic door that opens when it is approached by a virtual object (see figure 5.8).

This exploration uses a somewhat different setup than the previous examples. We use a steerable toy that approaches the door. Due to sensors above the door, the door opens when the toy moves in front of it. In order to turn the physical toy into a virtual object, an AR marker is placed on top of the toy. A combination of the Unity game engine and the Vuforia AR SDK is used to detect the marker in a live webcam feed of the environment. When the marker is detected, it is replaced by a virtual sphere. On the laptop screen, this makes it look as if a virtual ball was rolling towards the real door. The result works as expected: we see a virtual sphere that approaches a real door, and a real door that opens just like it would open for a real object or person.

Of course, our implementation of this scenario is not ideal. To realize this concept, we do not need a physical object or toy to open the door. Ideally, a virtual object could be made to appear in the environment, and if it approaches the door, a signal that opens the door

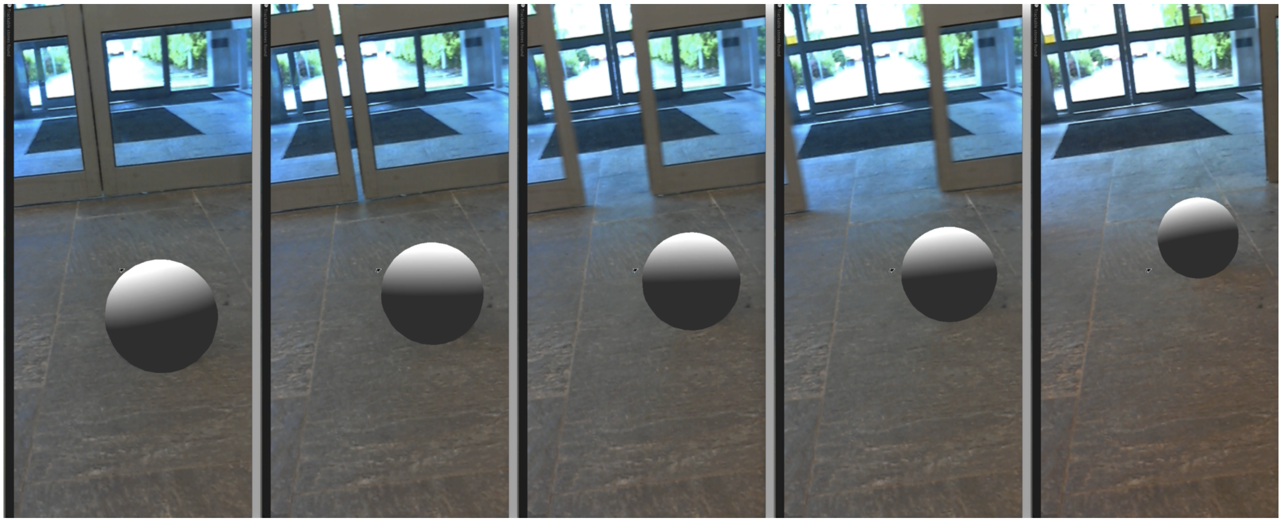

Figure 5.8: A real door opens for a virtual sphere. Image © Hanna Schraffenberger and Edwin van der Heide.

could be sent to the door. After all, the motion sensor above the door also sends such a signal to the door when a real person approaches it. Ideally, the virtual object would also react to the door, and e.g., stop and wait until it is open until it moves on.

In our opinion, this example is interesting because it makes use of a real object that senses the world and reacts to what it senses. In our experience, the fact that the real object seemingly senses the virtual object contributes to the feeling that the virtual object is actually part of the environment. Simply put: if the door sees the object, it has to be there!

We can imagine similar interactions between virtual objects and other real objects that are controlled by signals. As suggested by Barakonyi et al. (2004), virtual objects could, e.g., interact with printers, digital instruments and interactive robots as all of these objects can be queried for status information and controlled with commands.

5.2.2 *Imaginative Interactions*

The preceding imitative explorations have shown that in AR, at least some real-world interactions can be simulated between virtual and real objects. In the following, we explore influences between the virtual and the real that do not mimic reality, but instead, try to bring new imaginative and physically impossible forms of actions and reactions to the real world.

As discussed, the virtual does not have to obey physical laws (cf. Sutherland, 1965). Hence, it can behave in novel and *physically impossible* but—according to our hypothesis—*nevertheless believable* ways. Unfortunately, our review has revealed little examples to support this point. However, just as we accept imaginary objects with their own behaviors in books, computer games and movies, we expect that we can accept different sorts of objects and different forms of behavior in AR.

Whereas interactions based on imitating the real world present the challenge of making real objects behave realistically, imagination-based relationships between the virtual and the real not necessarily entail such a challenge. If we do not mimic specific realistic interactions, it might not be a problem if the real world has an effect on the virtual but is not affected in return. Accordingly, we believe an interesting direction to explore is the possibility of realizing simple one-directional influences rather than complex two-way interactions.

One challenge when it comes to exploring imaginative influences is the vast realm of possibilities. We can, for instance, easily imagine a virtual ghost that—unlike any real object—floats through real walls.[10] Likewise, we can envision virtual objects that change their size, color or shape when they collide with a real object or teleport to another position when they hit something real.[11] Furthermore, we can take inspirations from books and movies and, for instance, envision a virtual character that, unlike Pinokio, grows a longer nose whenever it hears a lie. Ultimately, the range of possible influences is only limited by our own imagination.

[10] One could argue that this is a lack of influences rather than a novel form of interaction. However, as real objects cannot move through real walls, we believe this is an exciting possibility to explore—no-matter whether one terms it interaction or not.

[11] For instance, the virtual object could 'take over' the color of the real object.

Of course, we cannot explore all possibilities at once. In the following, we explore this idea of physically impossible but nonetheless believable interactions in the context of *attractions* between virtual and real objects. The combination of virtual and real objects allows us to create new forms of 'magnetism' or attractive forces that cannot exist in a purely physical world. The choice to focus on attractive forces is simply based on the curiosity of the author, who always considered magnetism a fascinating phenomenon in the real world and who is curious to explore variations of this phenomenon in the context of a mixed virtual-real environment. In the future, the idea of inventing new laws can be explored in many other contexts. Whereas the virtual objects presented in the sections below still have quite some similarities with real-world objects (e.g., with physical marbles), chapter 6 takes the idea of imaginative AR and new forms of virtual objects even further.

As mentioned, the implemented attractions solely establish *influences* between real and virtual elements rather than some form of *interaction*. However, a participant can react to the behavior of virtual objects as well as affect their behavior through interactions with the real environment. In this sense, the virtual, the participant and the real world interact with one another. This is why we title the section *Imaginative Interactions* and place this idea under the umbrella of interactions between the virtual and the real.

Exploration 1: Attractive Colors

The first scenario explores a new and imagined way in which virtual objects can react to the real environment. In this experiment, virtual objects are attracted by real objects that have a similar color. (However, real objects are not attracted by the virtual objects in return.)

The concrete setup to explore this idea includes a cloud of small virtual spheres—half of them with bluish colors and the other half with yellowish colors. Furthermore, it includes one blue and one yellow rubber ball. As soon as the rubber balls enter the scene, they attract spheres of similar colors (see figure 5.9). According to our own impression, the relationship between the virtual and the real is easily understood, intuitive and believable although the virtual spheres do not imitate the behavior of real objects and do not obey the same physical laws as real objects. As expected, the fact that the virtual has no influence on the real is not a problem.[12]

[12] The virtual objects appear rather light in relation to the physical objects. This means that this lack of influence might be experienced as realistic.

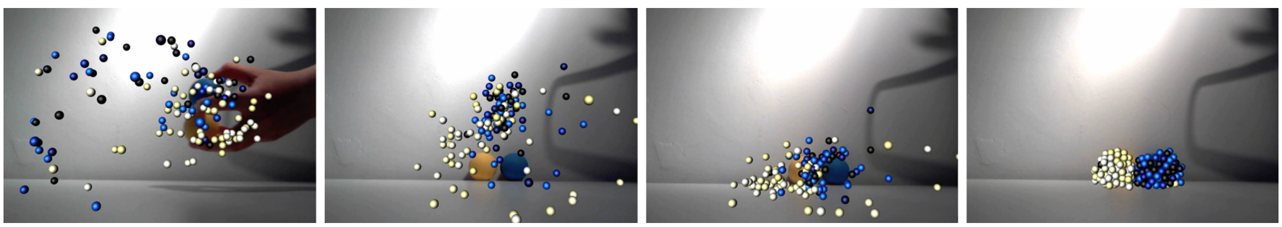

Figure 5.9: The colored rubber balls attract virtual spheres of similar colors. Image © Hanna Schraffenberger and Edwin van der Heide.

Even though the example is based on physical forces (attraction), it leaves behind the realm of realistic physical interaction as we know it. It becomes clear that the virtual does not have to behave like a real object in order to be believable.

Furthermore, the example shows that influences between the virtual and the real bring great possibilities for interaction between a participant and the virtual content: If physical objects influence virtual ones, the participant can interact with the virtual elements simply by interacting with physical objects.

Although imaginative interactions play an important role, the project also includes some imitative interactions. For instance, the virtual spheres roll over the table like real objects and block each other's way like real spheres do.

A nice aspect of this example is that the real balls can interact with each other, and, e.g., collide. These interactions between the real spheres, in turn, affect the virtual spheres that also interact. If the participant also starts to intervene, this setup can lead to complex chains of cause-and-effect that involve influences (1) between the two real spheres, (2) between real spheres and virtual spheres, (3) between virtual spheres, (4) between the participant and the real spheres, and indirectly, (5) between the participant and virtual spheres.

It should be noted that although this example aims at exploring potential color-based relationships, the virtual and real objects also shared the same shape. This might have an influence on our experience and, e.g., cause the scenario to appear more convincing. In the future, it might be interesting to look at the attraction between similar colors and similar shapes independently.

Exploration 2: Attractive Light

As a next step, we explore a setting where small randomly colored virtual spheres are attracted by real light. A small desk lamp serves as a light source that can be turned on and off. This allows a participant to interact with the virtual spheres by interacting with the physical lamp (see figure 5.10).

In the default state, the virtual spheres are placed on the desk. However, when a participant turns on the light, the virtual spheres move upwards, as if they were pulled up by the light. If the light remains on, the spheres cluster around (in front of) the light source.

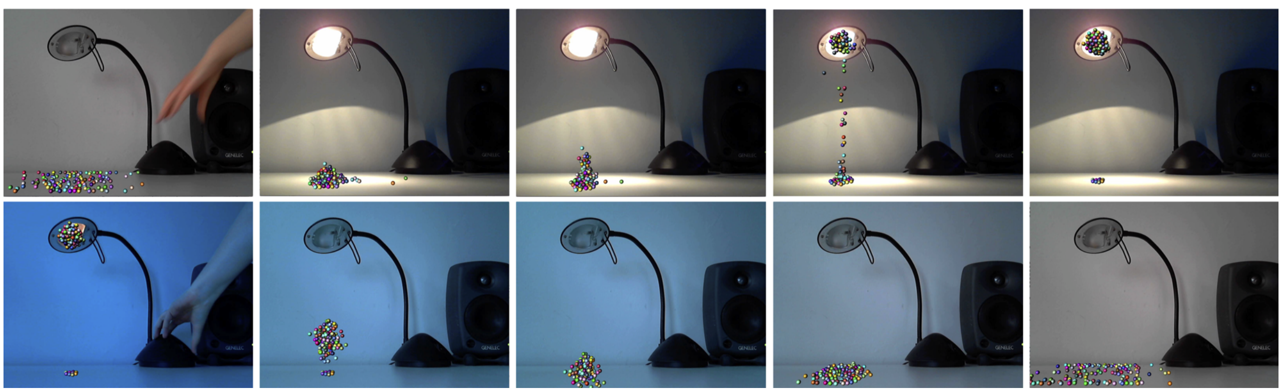

Figure 5.10: Virtual colored spheres are attracted by light. The top row shows what happens when the lamp is turned on (from left to right) and the bottom row shows what happens when the light is turned off. Image © Hanna Schraffenberger and Edwin van der Heide.

Admittedly, this project has some weak spots in its execution. First of all, when the virtual objects are pulled up, they can gain so much momentum that they 'shoot over the target', and momentarily move above the lamp, when one would actually expect a collision with the lamp. The fact that we expect a collision shows that we would actually like to see some imitative real-world interactions, even if the virtual objects display imaginative behavior. Secondly, the automatic color adjustment of the webcam feed is activated by the light changes, which causes the image of the environment to undergo weird color shading changes (e.g., the view becomes blueish when the light is turned off). Yet, in our opinion, the interaction between the participant and the lamp and the consequent response of virtual objects to the light, create a very strong sense of virtual objects being present in the space.

In our opinion, this scenario can be considered a gray area between both realistic and non-realistic interactions. On the one hand, simple physical objects like marbles are not attracted by and fly towards the light. On the other hand, the experience is supported by imitative interactions: the virtual spheres appear to collide with and roll over the desk like real spheres. Furthermore, we know similar (yet not identical) behavior from animals, such as moths who are attracted by light. It thus should be noted that the virtual spheres look like physical objects—not animals. Their appearance implies no creature like qualities. For instance, they do not have any apparent senses that would allow them to register the light. In addition, they also have no apparent way to move or act in the environment based on their own intentions. Instead, they look like tiny physical spheres. They roll over the real table as if they had a mass and they collide and interact with one another like physical spheres would. Yet, the resulting movement of the spheres occasionally reminds us of little creatures. In particular, when they are clustered in front of the light, they remind us of animals in a huddle that all try to achieve the same thing: getting close to the light. In the future, it would be interesting to explore when the implementation of imaginative laws leads to movements and actions that are interpreted as an active, goal-oriented *behavior* rather than physical cause-and-effect relationship.[13].

[13] Similar topics have been explored in the context of cybernetics for a long time. For instance, in the early 1950s, Grey Walter has presented so-called *Machina speculatrix*. These simple mobile robotic vehicles were equipped with two miniature radio tubes, a touch- and a light-sensor and two motors, and appeared to exhibit the "exploratory, speculative behavior that is so characteristic of most animals" (Walter, 1950, p. 43).

In the future, this example could be extended with sounds (especially when the spheres and the desk collide). A question that remains open is if such sounds would have to mimic the sound of small spheres dropping on a desk in order to be believable.

We can imagine this light-based form of interaction as a very intuitive and easy-to-learn way for participants to interact with virtual content. For instance, a participant could use a flashlight to attract virtual objects, move them around, and turn off the flashlight in order to let go of them.

Exploration 3: Magic Hands

This small project focuses on interaction between a participant and virtual content and addresses the issue of how participants can move virtual objects in space. Like previous examples, the project builds on the idea of new forms of attractions: Here, the hands of the participant (author) are tracked with a Microsoft Kinect camera and programmed to attract virtual objects. Unlike in previous examples, the computer monitor serves as 'magic mirror'. To see themselves interact with the virtual objects, the participant has to look at the monitor. The monitor shows a mirrored view of the environment that also contains the virtual balls.

To explore the ideas of having 'magnetic hands' that attract virtual objects, a large number of approximately tennis-ball sized virtual spheres are placed in the participant's/author's room. If the participant moves the hands close to the balls, they move towards and stick to the hands. By quickly moving the hands away, it is possible to let go of the balls. The screenshots of the resulting view in figure 5.11 show this effect. In addition to sticking to the hands of the author, the balls also seemingly defy physical laws in the sense that they move through the space in slow motion.

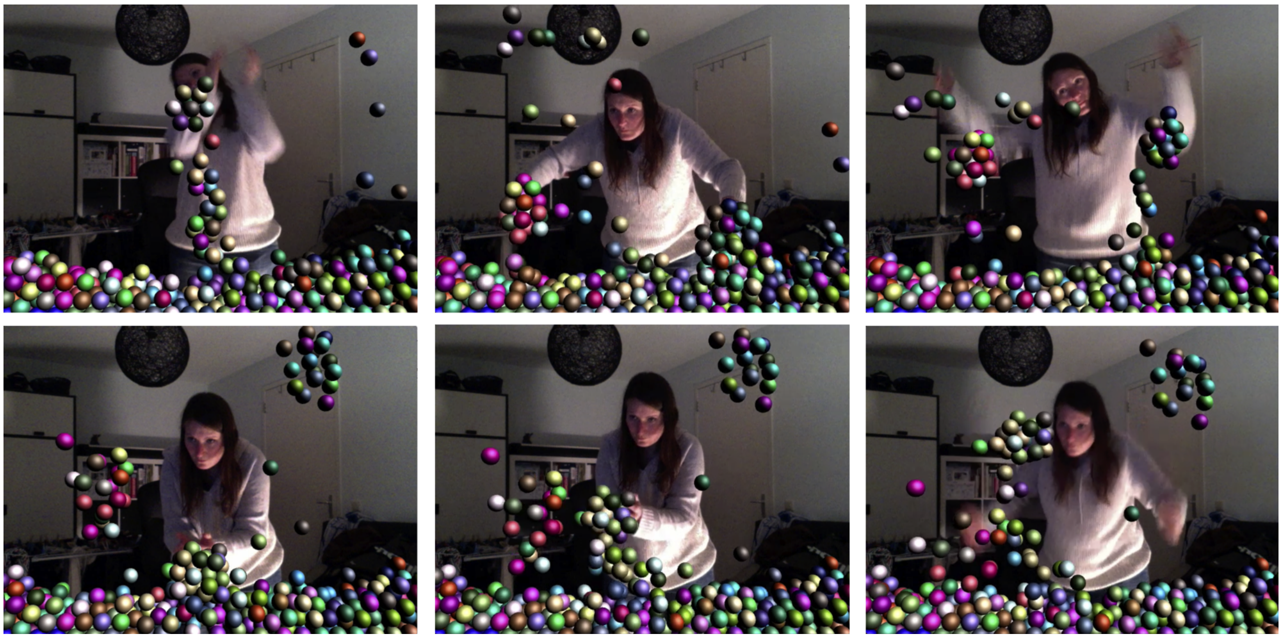

Figure 5.11: Virtual colored spheres are attracted by the hands of the author/participant. Quickly moving the hands away from the virtual balls allows one to let go off them. Image © Hanna Schraffenberger and Edwin van der Heide.

According to our experience, playing around with this form of interaction is extremely intuitive and the setup is very enjoyable. One of the observations that stuck with the author, is that the author intuitively adapted her movement, and started to largely move in slow-motion (however, using short and sudden movements to let go of the spheres). Seeing herself on the screen, she felt a strong urge to move in a believable way, and not, e.g., create motions that contradict the characteristic movement of the virtual spheres. This, e.g., also included holding the hands in a way that they looked properly covered by the spheres. It would be interesting to see if the same urge to behave believably and the resulting slow-motion movement is also found in other people.

We believe that 'magic hands' can serve as an easy means to facilitate interaction between virtual and real objects. For instance, one hand could be made to attract virtual objects whereas the other hand could be made to repel them. We expect this to allow for a lot of basic interactions, such as picking up and moving virtual objects in space.

5.3 *Discussion, Conclusions and Future Directions*

We have asked whether interaction between virtual content and the real world can imitate interactions that we know from the physical realm as well as take on new imaginative forms that have no equivalent in a purely physical world. Our theoretical and practical exploration has shown that both is possible but also challenging.

When it comes to realizing realistic interactions, we are facing a surprising dilemma: by making virtual objects behave like real objects, actual objects in the environment behave unrealistically. As S. Kim et al. (2011, cf.) show, this can, for instance, happen when a virtual ball collides with a real paper cup without causing this cup to move. A key question that arises in this context is how virtual objects would be able to affect the real world. We have identified four key ways to address this challenge and allow virtual objects to affect the real world.

First of all, the virtual can affect the real if the real world is extended by means of electronics such as actuators. The virtual can then move or transform the real by controlling these actuators. Likewise, one can modify those real objects that already are equipped with electronics and that already react to the environment. For example, we have suggested that automatic doors can be modified to also open when something virtual approaches them.

Second, we can extend physical objects with *virtual* qualities. This can make it seem *as if* real objects reacted to virtual objects. We have proposed a simple example where a real desk is extended by means of virtual sounds and thereby, can react (resonate) when it is hit by a virtual object. This idea could be taken to the extreme: For instance, if a virtual ball would hit a real window, we could make it look as if the window were broken, and if a virtual ball would hit a real cup, we could make it look as if the cup were moving. Of course, it is questionable if we should call a real window that appears to be broken, or a real cup that appears to move while it actually stands still, *real*. We propose to call such objects that unite both virtual and real qualities *augmented objects*. (The concept of augmented objects will be discussed in more detail below.)

Third, just like real objects can be extended with virtual qualities, virtual objects can be extended with physical properties. This, too, results in an *augmented object*. We have shown this in the case of a virtual sphere that we have extended with a physical ball.

Fourth, we can present virtual content in the real world directly and thereby utilize real-world interactions. For instance, we can play back the sounds of a virtual creature on loudspeakers. In this case, the sounds actually resonate in the environment. Likewise, the light of a virtual sun might be projected onto a wall directly, in which case the light from the projector actually lights up (and maybe even warms up) the space. In such cases, the boundaries between the virtual and the real blur: unlike the virtual creature and the virtual sun, the light and sounds actually exist in the environment, and thus, will interact with it.

While we have shown that that virtual objects can affect the real world, it also has become clear that this is not always necessary. We also can establish believable influences where the real affects the virtual but where the virtual does not affect the real in return. For instance, we have created an imaginative scenario where real objects attract virtual objects that have a similar color. Judging from our experience, this is convincing even if the real world is not affected by the virtual spheres.

Our review and exploration have shown that interaction between the virtual and the real can take place both in the virtual domain as well as in the physical domain. For instance, the voice of a virtual character can be played back in a church on a loudspeaker. In such a case, it is *actually* affected by the characteristics of the surrounding space and the interaction thus takes place in the physical domain. However, we might also play back the sound on headphones and apply virtual reverb to the voice. This would only make it seem *as if* the voice were affected by the church and the interaction would thus take place in the virtual realm. Both forms can be desirable. For instance, when shooting virtual bullets, the bullets should arguably only *seemingly* have an effect on the world. On the other hand, when playing bowling with a virtual ball and real pins, it might be quite entertaining if the real pins would actually fall down upon being hit. When designing AR environments, we thus have to carefully consider these possibilities.

As discussed in chapter 3, a common goal in AR is to make it seem as if virtual objects were a part of the real environment. Judging from our own experience, interactions between the virtual and the real can play a crucial role in making it seem as if a virtual object were actually present in the real world. For instance, the fact that an automatic door opens for a virtual object can reaffirm our impression that the object is part of the space. Likewise, virtual objects that stick to our hands can give us the feeling that they are present in space 'with us'. In the future, it would be interesting to further explore the effect of such interactions on the experienced presence of virtual objects in real space. We expect that the lack of interactions between the virtual and the real can also harm the illusion of virtual objects being part of the real environment. If, for instance, virtual rain does not cause the real world to get wet, we might not feel like the rain is a part of the environment.

As our review has shown, it is sometimes assumed that virtual objects should obey to physical laws and interact with the world in the same manner as real objects. Judging from our current exploration, this is not always necessary. In our opinion, what matters is not whether something can exist in the real world but whether it is believable.

5.3.1 Augmented Objects

As mentioned above, we have proposed to extend virtual objects with physical properties and to extend physical objects with virtual properties and have coined the result *augmented objects*.[14] We believe that augmented objects can play an important role in facilitating interactions between the virtual and the real. Augmented objects share qualities with both virtual and real objects and consequently, can interact with both virtual elements and the real world. Our exploration has shown that augmented objects can be used to apply forces to the real world just like real objects. Furthermore, we expect that augmented objects can change their visual appearance, such as color, texture, size and to some degree shape just like virtual objects. Similarly, they can likely create sounds that differ from the sound of physical objects. However, at the same time, augmented objects also lack many of the possibilities of virtual objects: An augmented object can, e.g., not hover through space, teleport or move through walls. It might also cause a natural sound that cannot easily be 'removed' from the environment. Which of these qualities are considered advantages and which are considered disadvantages likely differs from project to project and depends on the actual context and goal of a project. In the future, it would be interesting to explore the possible manifestations of augmented objects more systematically.

[14] An augmented object is similar to the hybrid objects defined in section 4.5. However, when it comes to hybrid objects, the virtual and the real complete one another and both serve as an integral part of the object. When it comes to augmented objects, the virtual adds something additional to a real object but not necessarily completes it. We hence see augmented objects as a more general umbrella that describes objects with both a virtual and a real component.

The idea of working with *augmented objects* in AR is not new. In our theoretical exploration, we have encountered examples that extend physical objects with virtual qualities. For instance, Bau and Poupyrev (2012) have extended physical objects with virtual textures. Likewise, Sphero—the robot ball that can take the form of a virtual beaver—is based on the idea of extending a physical object with a virtual character. In addition, we have seen projects that extend virtual content with a physical dimension. So-called 'tangible interfaces' (Billinghurst, 2001; Billinghurst, Kato, and Poupyrev, 2008) link a physical and tangible element to virtual objects. However, to the best of our knowledge, the AR research community has only addressed such concepts in the context of interaction between a *participant* and virtual content. In contrast, we have also focused on interaction between the real general environment and virtual content. This has shown that augmented objects can interact with physical objects as well as allow participants to interact with them.

The concept of augmented objects—objects which combine virtual and physical qualities—also raises more fundamental questions about the nature of virtual content: One could argue that every perceivable virtual object is an augmented object. This is because every perceivable virtual object has some physical counterpart that allows us to sense the object. For instance, a virtual sun might be shown to a participant via pixels on an AR head-mounted display and virtual rain might be represented with the sound of raindrops. The sun and the rain thus have a physical representation in the form of light or sound. If we follow this line of thought, every virtual object is actually an augmented object and falls somewhere onto a spectrum between entirely real and entirely virtual.

5.3.2 *Participant-Content Interaction*

In existing research, interaction between a *participant* and virtual content and interaction between virtual content and the real *environment* are often addressed independently. In this chapter, we have proposed to see the participant as a part of the real environment. In our opinion, this approach has been successful: our explorations have resulted in scenarios that facilitate both. We have seen that if virtual objects interact with the real world, participants can interact with the virtual content by interacting with the real environment. For instance, if virtual objects are attracted by light, a participant can interact with them by using a flashlight, closing the curtains or turning on the light. Likewise, if virtual objects are attracted by real objects that have the same color, a participant can interact with virtual objects by moving around real objects. This shows that by establishing influences between virtual objects and the real environment, we can also facilitate the often-desired interaction between a participant and virtual content. We hope to further explore the complex dynamics between a participant, their real surroundings and virtual elements in this space in the future.

5.3.3 *Future Directions*

When it comes to imaginative influences and interactions, a key issue is believability. Presumably, not everything that we can imagine is also credible. So far, our exploration has only taken the individual experience of the author into account. Of course, this experience might be biased and does not necessarily tell us anything about how other people would experience the different scenarios. In the future, it would be desirable to explore the different scenarios with other participants and address whether they are experienced as believable. Another topic that could be addressed in this context is the 'physical artifact' (S. Kim et al., 2011). More generally, it would be interesting to know how we experience real objects that appear to display an 'unrealistic' behavior. How do we feel when a real mirror does not reflect the virtual creatures that sits in front of it? How do we experience a real cup, when it does not move after being hit by a virtual object (cf. S. Kim et al., 2011)?

A more general goal for the future will be to understand what factors contribute to whether the interaction between virtual and real objects is perceived as credible. We assume that what is experienced as believable is closely linked to our expectations as well as to the appearance and behavior of a virtual object. Presumably, if a virtual object looks so realistic that we mistake it for a real object, we also expect it to also affect the real environment just like a real object. However, virtual objects do not have to look like real objects and in such cases, we might not have such expectations. As mentioned in the introduction of this chapter, we expect that the believability of an object's behavior is linked to the situation and context in which it is presented. For instance, we expect different behaviors to be believable in a gaming context than in an educational context. A possible next step would be to place our proposed interactions in different contexts (e.g., as part of a game) and evaluate whether they are believable in different situations. More generally, future research can address whether and how the context in which a behavior takes place affects the believability of this behavior.

This chapter has focused on the behavior of virtual and real objects *with respect to one another*. In the future, it would be interesting to also address believable *behaviors* of virtual objects in the real world that are not related to any real object. For instance, it would be interesting to know whether we find it believable if virtual objects teleport, change their size, color, shape without any apparent real cause.[15]

[15] With respect to realistic and imaginative qualities of virtual objects, it would also be interesting to implement virtual versions of so-called "supernormal stimuli" (see, e.g., Staddon, 1975). A supernormal stimulus is an imitation of a real-world stimulus that differs substantially from the imitated stimulus and that is not encountered naturally in the real world. Supernormal stimuli have, e.g., been studied in the context of animal biology, where it has been demonstrated that animals can respond stronger to such (e.g., exaggerated) imitations than to the natural imitated stimuli. Augmented reality opens up many possibilities to design virtual supernormal stimuli and place them in the real environment. Studying participant responses to such stimuli might be particularly interesting in the context of biology, psychology and perception research.

So far, our exploration of imaginative influences has only addressed new forms of attraction between the real world and virtual content. However, many more forms of imaginative laws and behaviors can be explored. As mentioned, virtual objects could change their shape or color whenever they collide with a real object. Likewise, they could teleport to another position. It might also be interesting to play with the time-dimension, and e.g., rewind the movement of a virtual object after it collides with a real object. Future research can address whether such interactions are credible and meaningful.

Furthermore, our exploration has focused on simple physical objects so far. In the future, it would be interesting to explore the more specific case of virtual characters that have their own senses and pursue their own goals.

In the course of this exploration, we have focused on visual AR. In the future, it would be especially interesting to explore the possibilities of non-visual, multimodal and crossmodal interactions and to include other physical properties of the environment. For example, real wind might move virtual leaves and the temperature of the environment might affect the behavior of virtual creatures.

This chapter has focused on interactions between the virtual and the real. Although many virtual objects used in our explorations have reacted to the real world in new and imaginative ways, they have still imitated real objects and the physical world in many ways. In particular, the virtual spheres used in our experiments still *look* like a lot like spheres that actually can exist physically. This makes us wonder whether and to what degree virtual objects can differ from real objects. We will explore this question in the next chapter and attempt to create an object that does not look, feel or behave like any real object.

To conclude, we propose there are two worthwhile approaches to creating influences and interactions in AR: On the one hand, the imitation of reality. On the other hand, the creation of imaginative realities. Whereas the first has gained a lot of attention, the latter has gained little attention so far. We hope that our research serves as a fundamental step towards new kinds of realities in which the virtual and the real interact in unique and creative ways.