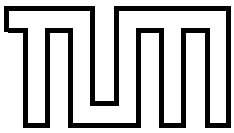
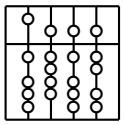


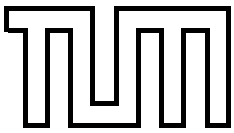
Technische Universität München
Fakultät für Informatik



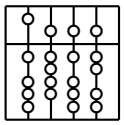
Master's Thesis

Analysis of Conceptual Differences and Similarities Concerning the Interaction with Physical and Digital Objects in Augmented Reality

Christian Trübswetter



Technische Universität München
Fakultät für Informatik



Master's Thesis

Analysis of Conceptual Differences and Similarities Concerning the Interaction with Physical and Digital Objects in Augmented Reality

Christian Trübswetter

Aufgabenstellerin:

Prof. Gudrun Klinker, Ph.D.

Betreuerinnen:

Prof. Gudrun Klinker, Ph.D.
Dipl.-Inf. Verena Broy

Abgabedatum:

16. August 2005

Ich versichere, dass ich diese Master's Thesis selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel verwendet habe.

München, den 16. August 2005 Christian Trübswetter

Zusammenfassung

Diese Arbeit möchte aufzeigen, inwiefern sich physische Objekte, wie sie in unserer wirklichen Welt existieren, von digitalen Objekten unterscheiden, die von einem Computer erzeugt werden. Diese Unterschiede schaffen Barrieren zwischen digitaler und physischer Welt. Der Forschungszweig "Erweiterte Realität" beschäftigt sich mit der Anreicherung unserer gewohnten physischen Welt um digitale Elemente. Dort sind solche Barrieren allgegenwärtig. In dieser Arbeit wird versucht, auf systematische Art und Weise die den physischen und digitalen Welten innewohnenden Eigenschaften zu finden und zu erklären.

Eine Analyse wird aufzeigen, welche dieser Eigenschaften in beiden Welten existieren und welche eher in einer Welt anzutreffen sind. Es werden Wege aufgezeigt, wie die Eigenheiten der Objekte einer Welt in der anderen Welt simuliert oder ersetzt werden können. Anschließend wird dargelegt, wie physische und digitale Objekte miteinander zu gemischt physisch–digitalen Objekten verbunden werden können. Darüber hinaus werden Beispiele angeführt, die zeigen, wie Gruppenarbeit durch solche gemischten Objekte profitieren kann.

Schließlich wird eine exemplarische Anwendung für die Erweiterte Realität entworfen, die sich der gewonnenen Erkenntnisse bedient.

Abstract

The aim of this Master's Thesis is to find out to what extent physical objects in our real world differ from digital objects that are created by a computer. These differences create barriers between the digital and the physical world. The field of augmented reality, in which the physical world is enhanced with digital elements, must cope with the imposed barriers. This work tries to systematically find and explain the inherent characteristics of both physical and digital objects.

There will be a analysis on which characteristics exist in both worlds and which ones are more closely related to one world. Ways are shown how to simulate or replace the exclusive characteristics in the opposite worlds. It will be pointed out how digital and physical objects can be interconnected with each other in order to form mixed objects. Furthermore, some examples will be given how collaborative work can benefit from mixed objects.

Finally, an exemplary augmented reality application will be designed which makes use of the gained insights.

Preface

About this Work This work was performed as a master's thesis in computer science at the Technische Universität München (TUM). My supervisor was Prof. Gudrun Klinker Ph.D. who also advised me together with Dipl.–Inf. Verena Broy.

Acknowledgements I would like to thank Gudrun Klinker and Verena Broy for supporting me in realizing this Master's Thesis. Our weekly meetings were always very interesting and we had discussions on quite visionary topics. I want to thank you for giving me an insight into your understanding of the (physical and digital :-) world, and for giving me the necessary freedom in developing my own ideas. Finally, thank you for giving me advice and feedback during the writing of this work.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation

Augmented reality is an evolving subject area of computer science and other disciplines. Its idea is that the real world we live in can be augmented by objects that do not exist physically, but rather in the computer. Within this work we will call them digital objects, whereas the real world objects will be called physical objects. A more exact definition and a discussion on the definition of these terms will be given in section 1.3.

In order to see digital objects within our physical World, they have to be displayed somewhere and overlaid with physical objects. Figure 1.1 shows how this can be achieved. A currently filmed scene can be augmented on a computer monitor or a handheld display(see figure 1.1a,c). A head mounted see–through display performs augmentations on a transparent LCD (1.1b). Digital objects can also be directly projected onto physical objects in the real world (1.1d). It is also possible to combine different displays within one application (1.1e). Digital objects can provide us with additional information, for example on the scene we see, or they act as digital metaphors. In many augmented reality applications, digital objects are controlled by real world objects. For example, we could move a digital teapot on a physical tablet. Digital objects themselves can control or at least have influence on other digital objects. We know that from computer games: a digital figure can move objects, which itself can trigger other events. Also the inverse functionality is possible: the digital objects are used to control objects of the real world. They are used as a kind of controller. In that case so–called actuators are necessary to transform the digital events into physical ones. In a factory we might open and close physical valves by manipulating digital valves or icons of them that are linked with the physical ones.

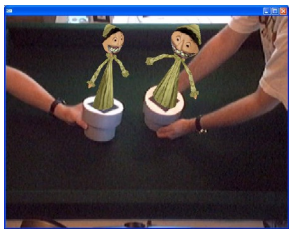
1.1.1 Scope of this Thesis

Within the last years, a lot of projects have demonstrated the usefulness of augmented reality in a vast range of areas. Augmented reality software for prototyping, 3D drawing, and authoring has been developed.

There are still a lot of technical problems to solve, mainly related to the tracking of objects and displaying them. That is why most projects address technical problems. Also data structures, software architectures, and design patterns for augmented reality have been developed in the recent years.

Often, augmented reality projects focus on one specific area. That is why improvements in the application domain usually take a big share of the development time.

In most augmented reality projects the right digital objects have to be placed at the correct position regarding a display or the viewer. Therefore, trackers are needed. Much effort has



a) Typical augmentation on non-transparent displays

b) Augmentation with see-through head mounted display

c) Mobile augmentations

d) AR on table

e) Multiple coherent displays

Figure 1.1: Augmented reality applications with different display systems

been put into the development of different kinds of trackers. In most cases, it became evident that the demands made on appropriate tracking are the hard to fulfill. The restrictions of tracking systems are the reason for most limits and failures of augmented reality systems. A considerable part of current projects deal with adapting and improving trackers. A further area, in which great efforts have been made, deals with creation and improvement of visualization and the development of new kinds of displays.

This thesis abstracts from technical difficulties of tracking and displaying by assuming that these may either work accurately to a sufficient degree that they work with some failure or that they do not work at all for some time. It considers them as inherent characteristics and not as disturbing side effects; this thesis does not focus on the improvement of tracking or display technologies. Although this work is not focused on a specific application domain, it contains various illustrative examples. The central theme of this work is about bringing together physical and digital objects, without caring too much about current or permanent technical difficulties.

1.1.2 Introduction to the Theme

Augmented reality has shown that it makes sense to think about way to use digital and physical objects conjointly within one application. Before doing that, it has to be clarified how digital and physical objects can be defined and what kind of characteristics they have. Once this is done, the differences between both worlds become evident and can be compared systematically with each other.

As long as digital and physical worlds are not or only loosely combined, these differences have only few negative implications. When both worlds are linked with each other, however, difficulties arise. Due to immanent differences, physical and digital objects may behave in an undesired manner, when some property or the kind of interconnection is changed. These differences, no matter whether they are intended or unwanted, can lead to conflicts, inconsistencies, or ambiguities. These must be treated in a certain way. In most cases there will be a variety of ways in resolving such problems.

A small example should illustrate that. Imagine a scene that only consists of one physical cube and one digital cube. The digital cube shall always have the very same position and orientation the real cube has. Now, for some reason the real cube is not detected anymore. This could be a tracking problem: a bad tracking algorithm, bad light conditions, the breakdown of a tracking camera. Maybe the cube was moved outside the tracking area. The cube may have been broken, or it is completely lost or destroyed. The result is that the real cube has no position any more, or at least an unknown position. The question is, what to do with the digital cube. We could imagine several possibilities:

- The digital cube could be destroyed.
- Or it could be hidden from the user.
- It could be displayed at a position in the scene where lost objects are shown.
- It could also be displayed at its last known position or at a position that is extrapolated from the real object's trajectory.
- Some very fancy tracking algorithm could detect that the cube was split up in two parts. The digital object could then do the same.

As it can be seen, there is often more than one solution to a conflict, sometimes even an unlimited or uncountable number. In most cases the application domain will decide, which kinds of solution make sense.

The idea of this work is to give a systematic analysis of differences between physical and digital objects. The implications of these differences on different coupling models are investigated and solutions are proposed for some of them. Finally, specific problems will be addressed that arise from collaboration.

1.2 Structure

Chapter 1: Following the last section on this work's motivation and this section on the structure, the words that are fundamental to this work will be discussed. It will provide

the reader with the definitions for essential terms like ”physical object“ or ”digital object“ as they are used in the context of this work. It will be explained, why these terms and not others have been chosen to name a certain context.

In the following section, an introductory example about slips of paper is developed that compares digital, physical, and mixed objects. The example will give a first insight into the subject of this work and should serve as a motivation for the following chapters.

The next three chapters are the most central in this thesis:

Chapter 2 identifies the most important characteristics of physical objects. We will see how these characteristics can be measured and transformed so that they can be processed digitally. It will also be explained how the physical aspects can be simulated for digital objects.

Chapter 3 focuses on additional characteristics and concepts that can be found in digital objects or — more generally — in software. We will evaluate the possibilities that these objects provide. Furthermore, we will mention to what degree they can be transferred to physical objects.

In chapter 4 we will look for ways of creating mixed objects. This is done by connecting physical and digital objects with each other. There exist various forms of connecting them. We will also see that differences in physical and digital characteristics can lead to inconsistencies, ambiguities, and some other problems. We show how big the variety of mixed objects is and we will also try to find creative solutions to the identified problems.

Chapter 5 deals with different kinds of collaboration. We will see different concepts and ideas of collaborative software. Based on that, new ways of collaboration with mixed objects are evaluated by combining the ideas of traditional and software related collaborative work.

Chapter 6: In order to demonstrate how the insights gained in the previous chapters can be of use, a little augmented reality application was designed. The program was tested with variations of physical, digital, and mixed objects. The advantages and disadvantages of the single variations were also analyzed.

Chapter 7 eventually provides the reader with the most essential findings of this thesis and gives a short outlook into the future of mixed and augmented reality.

1.3 Definitions

Throughout the augmented reality literature, the fundamental terms are not completely fixed yet. For some concepts there are a variety of words that do not necessarily correspond

exactly. In the following paragraphs, the most central terms are defined as used throughout this script. In addition to that, the most important alternatives are discussed.

1.3.1 Augmented Reality

A definition of "*Augmented Reality*" is given by Professor Gudrun Klinker:[1]

> Augmented Reality (AR) is a newly emerging technology by which a user's view of the real world is augmented with additional information from a computer model. With mobile, wearable computers, users can access information without having to leave their work place. They can manipulate and examine real objects and simultaneously receive additional information about them or the task at hand. Using Augmented Reality technology, the information is presented three-dimensionally integrated into the real world. Exploiting people's visual and spatial skills to navigate in a three-dimensional world, Augmented Reality thus constitutes a particularly promising new user interface paradigm.
>
> Research in Augmented Reality and wearable computing is beginning to receive more and more attention due to striking progress in many subfields and fascinating live demonstrations (due to advances in computer miniaturization, mobile networking, and sensing technology). Augmented Reality, by its very nature, is a highly inter-disciplinary field, and Augmented Reality researchers work in areas such as signal processing, computer vision, graphics, user interfaces, wearable computing, mobile computing, computer networks, distributed computing, information access, information visualization, software engineering, and the design of new displays.

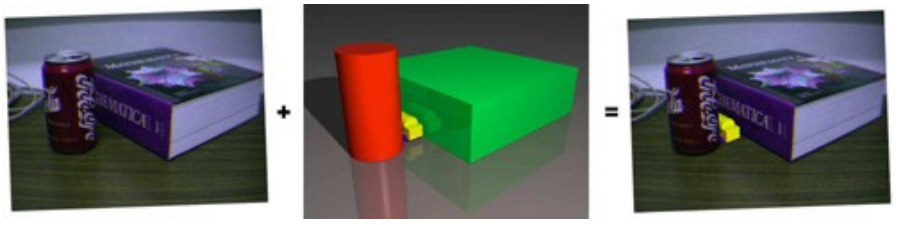
The first picture in figure 1.2 [29] shows real world objects, the second picture shows a virtual reconstruction of these objects plus additional objects (yellow object). In typical AR applications, the real world is enriched with such additional objects or information.

It can be seen that augmented reality enables to embed digital objects into the real word. Therefore, real objects have to be tracked (which means their position and orientation has to be determined, usually in real–time). Based on this information and on additional information such as the shape of the single objects, a digital model can be created. Additional components, for example textual information, graphical user interfaces, or additional objects can be integrated into this model. Their appearance from the user's point of view can be computed, possibly with realistic lightning and overlapping. Thereafter, these components are displayed on the user's view.

1.3.2 Physical and Digital Objects

It is not easy to decide on a term for the two concepts that in this work are named "physical object" and "digital object". In literature, there exist different words for both concepts and the concepts also slightly vary. A different naming also leads to a different perception of a

[1] Definition taken from the Augmented Reality Homepage at [29]:



a) Real World b) Digital reproduction and extension c) Augmented Reality

Figure 1.2: Illustration of augmented reality

concept because the terms are also used in everyday language. Though hearing a word in a special context, a person will automatically associate something that comes along with its everyday meaning.

1.3.2.1 Alternatives for the term "physical"

First we want to describe physical objects that exist in the real world. The most common synonyms for "physical object" throughout augmented reality literature are "real object" or "materialized object". Typical representatives of this concept are, for example, cubes, glasses, books, teapots but also houses, mountains, the ground we stand on, and even liquids and gases. In short, everything that consists of matter. In order to be used in augmented reality, the pieces of matter have to be tracked or at least some data about them have to be made available. These data are used in augmented reality applications.

The term "real": Definitely, "real object" is the most–used term for this concept. However, the word "real" is somewhat fuzzy and not so easy to define. Most people have a different impression of what is "real" means and what is does not. Some people argue that also digital objects in a computer program are "real". And in fact they are. Software is also reality. The term augmented reality implies that the concept of reality should be augmented with additional objects that are not real in the original meaning of the word. So it may not be an optimal idea to choose this term for differentiating between matter and software.

The terms "materialized" and "material": Sometimes the term "materialized object" is used. The idea is that — as stated before — all objects that consist of matter should be described. However, the word "materialized" gives the impression that such an object could also exist in a not materialized form; that it has the ability to materialize. Another problem with this word is that it is relatively long and hard to pronounce. So maybe "material object"

would be more appropriate, though it is not used very often in literature. Moreover, it is often seen in connection to "materialism", what is a rather different aspect of the word.

The term "physical": Prof. Ishii and Brygg Ullmer, widely known in augmented reality, often use the word "physical". In their work the word "physical" is also part of some neologisms. For example, physical icons are called "phicons", physical widgets "phigets". The core of the term physical is that the objects to describe have physical properties like color, mass, position, temperature etc. So the word physical characterizes very well the concept of these kinds of objects.

Decision: Though we favor the term "physical", it has to be mentioned that also this word can be doubted about. A lot of people see "physical" as the contrary to mental or psychological. Furthermore, the term "real object" is already very familiar to a lot of people. Additionally it is used in related terms like "real world" and "reality model" (Definition of "reality model" see below). Considering all that, in the following the term "physical object" is used for the explained concept. Additionally, the terms "real world" and "reality model" are used in parallel with the terms "physical world" and "physical model".

1.3.2.2 Alternatives to the word "digital"

The next task is to find a term for objects that exist in the computer and that are used in augmented reality to extend the user's reality.

"virtual" is the word most frequently used. Most people know the term virtual reality and can imagine what virtual objects should be. The original meaning of "vitual" in old english is "possessed of certain physical virtues" (dict leo org). Usually, it means "possible", "hypothetical" or "imaginary". This does not fit so well to data that are stored in a computer, because digital objects are neither hypothetical nor imaginary.

The term "digital": Another possibility is the word digital. Most people associate electronics and computers with this world. The form in which data that is stored in memory is also frequently termed "digital". As objects "in a computer" are represented in this form, this naming seems to be acceptable. From now on these objects will be called "digital objects". The only problem discovered for this term is that an augmentation of a physical scene could be realized as an analog projection of a physical object, using mirror effects of glass plates, for example. In this special situation, the term would be misleading.

1.3.2.3 Final remarks on the terms "digital" and "physical":

The question may arise why the pair "physical – digital" is favored over typical antonyms. Physical and digital are not contrary terms like most people will think of with the terms real and virtual. Interestingly, real and virtual were no antonyms until the term virtual world was invented.

In the beginning this choice may be somewhat confusing, but on it is also an advantage: the new antonyms are used in this new context and make clear that they have different meanings compared to the original meanings.

Table 1.1 gives an overview of antonyms and shows in which context they are used.

Concept	Opposite	Meaning	Examples	Typical areas of use
Digital	Analog	Storing or transmitting data in a discrete form in contrast to a continuous form	CD vs. LP; digicam vs. analog cam; DVB (digital video broadcasting) vs. traditional TV broadcasting	Electrotechnics, Information technology, features of technical devices
Physical	Psychical, mental	Related to the human body in contrast to the human mind	Body vs. brain; arm fracture vs. claustrophobia	Medicine, psychology
Material	Immaterial, ideological	Of immediate physical or economical value in contrast to ideational values	property, money vs. knowledge, education, arts, humanity	Economy, sociology
Materialized/material	Not materialized, immaterial	Consisting of matter in not in another form	Matter vs. energy, light (in classical physics);	Physics
Real	Virtual, fictious	Existing in our world the and not our imagination	Yak vs. Yeti; Clint Eastwood vs. Lucky Luke;	Philosophy, Literature
Physical (real)	Digital (virtual)	Consisting of matter in contrast to existing in the computer	Book vs. internet site; Board game vs. computer game	Augmented, virtual, mixed reality

Table 1.1: Ambiguities and antonyms of frequently used keywords

1.3.3 Reality Model

This work deals with interaction of physical and physical objects. However, these different objects are separated from each other, so that they cannot interact directly with each other. The digital object is in the computer and the physical object is in our real world. In order for the digital objects to get information on the physical objects, sensors are necessary. Sensors receive data of the real world. The data need to be digitized so that a computer can read them and work on them. Sensors can be cameras, weighing machines, velocity sensors, chemical sensors, anything that gets data on the physical world. A tracking system is a special kind of sensor. It tries to recognize and monitor real world objects.

There is still a gap between the sensor data and the digital objects. A model of the physical objects needs to exist that a computer can understand. This model is called reality model.

The data from the sensors are used to compute data that are assigned to the reality model. An example should illustrate that:

Reality model of a tennis ball: Imagine that we have a tennis ball and three "sensors": a camera, a balance, and a ruler. The reality model of this tennis ball be an instantiation of the class "tennis ball". This tennis ball has the attributes "position", "orientation", "color", "radius", and "weight". It should become clear that the reality model is just a model. It is a reduction of the reality and can contain errors. Our tennis ball model, for example, just contains the attribute color. The reality model of the tennis ball can not deal with a two-colored tennis ball.

Furthermore, some aspects of the ball are assumed to be constant. The balance is used once in order to measure the weight of the ball, but the weight is not permanently monitored. The attribute weight is simply set to the measured value. We assume that the position of the ball can be computed out of the video picture that the camera provides. This should happen in real time. There may be no possibility to get the orientation of the position of ball. It is typical for tracking systems that not all information are available all the time.

1.3.4 Summary

We have now defined the keywords for this work. Figure 1.3 illustrates them in their context. Please note that not all components that are essential for augmented reality are shown, but only that ones that were relevant within this section.

1.4 Related Work

This thesis has a relatively broad approach to augmented reality. It tries to analyze as many aspects of digitality and physicality as possible and compares them. Therefore, a relatively wide spectrum of research areas are related to this work. On the other side, it does not focus deeply on single issues of augmented reality.

Fields of related research: Everything that is subsumed under the topic of augmented reality is central to this thesis. Most ideas and concepts covered in this work are derived from augmented reality research groups and projects, but also other research areas take some share. Most of them, however, have a strong intersection with augmented reality.

This work uses concepts and ideas from the fields of visualization technologies, computer supported collaborative work, human–computer interaction, and engineering.

Handling of related work: Often when referring to other persons' work, we will ignore the restrictions of their solutions. Instead, we will use the ideas and inventions in the aforementioned research areas as a base of to fire our imagination and we will not bind ourself too much on technological limits. We will sometimes broaden the original intention of a certain work, or giving it a new direction, yet sometimes taking it out of its context and applying

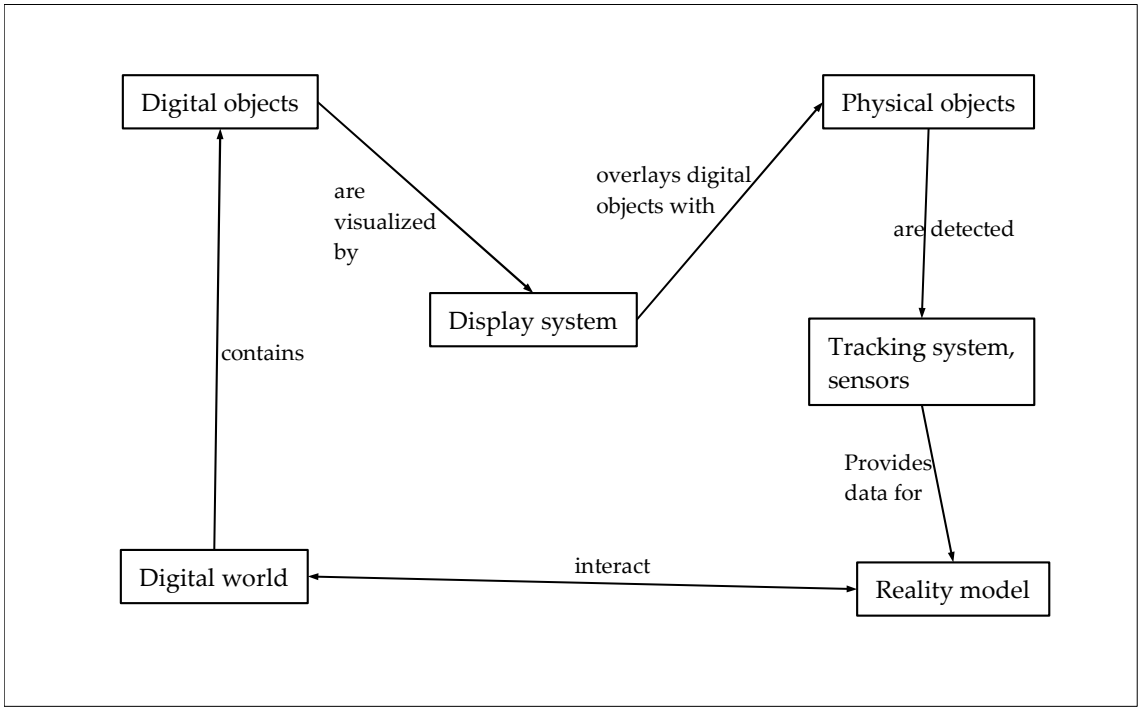


Figure 1.3: Defined keywords in their context

it in a new way. Hopefully, the the original inventors do not feel their concepts to be too heavily misused. For this work, though, a bit of fantasy and imagination is more important.

Some ideas do not strictly follow some existing theory, but they are derived from logic reasoning, common sense, and a systematic combination of given aspects. Some of them can be considered as thought experiments.

Augmented reality references: The understanding of augmented reality in this thesis is strongly influenced by Gudrun Klinker [29] and Vereny Broy, due to intense discussions during the creation of this thesis. The augmented reality projects for students offered by Mrs. Klinker enable an easy and very good introduction to this topic. So did especially the Fixit project [30], which I participated. She also gave me hints and recommendations for most of the following people and research groups.

Hiroshi Ishii [56] and his group at MIT Media Lab [38] defined a new kind of user interface for augmented reality with his work on tangible user interfaces. Often, augmented reality applications almost degenerate to virtual reality applications, as only very few and hardly different physical objects are used for interaction. It is the contrary with tangible user interfaces. Together with Brygg Ullmer, Ishii delivered very interesting ideas on how physical objects can act as metaphors, bringing more physicality into augmented reality. Therefore, very interesting ways of connecting physical with digital objects can be found in his work.

The second very inspiring work was done by Wendy Mackay [14] on augmented paper in

general, and recently on augmenting paper flight strips for air traffic control [34]. In reading her work, it becomes clear that that physical paper definitely has benefits that can not fully be replaced by software. She gives interesting ideas on how to work with textual artefacts in augmented reality.

Morton Fjeld [19], with his idea on using bricks in augmented reality, showed how to combine multiple physical and digital objects.

Furthermore, interesting ideas to this work could be found in several of Dieter Schmalstieg's [50] Studierstube projects [59]. Also the projects of Steve Feiner at the User Interfaces Lab at Columbia University [16] provided some new insights, here to mention his current work on augmented excavation.

Visualization: In order to visualize digital objects, displays are needed as well as methods for displaying them. Correspondingly display technologies and computer graphics knowledge are needed.

Some computer graphics knowledge is needed to understand how digital objects are displayed and how they can be represented. The ideas on visualization used in this work do not go beyond that of a standard book on computer graphics, for example that of Christoph Zenger [65], which I used.

This work mentions some displays types used for augmented reality, for example head–mounted displays, PDAs, and video projectors. We will not focus on display technology, but rather compare the different kinds of displays regarding their use in collaborative environments in chapter 5. I had the chance meet Wolfgang Stuerzlinger [60] from York University, Canada, who developed MULTI, a Multi–User Laser Table Interface.

Human–computer interaction: Two standard books on human–computer interaction were used for getting some inspiration on that topic: Ben Shneiderman's "Designing the User Interface" [51], and Judy Preece' "Human–Computer Interaction" [46]. A lot of concepts can be discovered that were proposed, but have never found its way into traditional windowing systems. Some of them might find a revival in augmented reality, for example, self–organizing non–overlapping windows.

From the augmented reality researchers mentioned before, it is Wendy McCay and Hiroshi Ishii, who develop their applications with focus on improving human–computer interaction.

Quite a lot of human–computer interaction projects cover collaborative themes, and nearly all of the aforementioned research groups have projects on collaborative. This will be of use when developing an augmented reality application in chapter 6.

Mechanical and electrical engineering, electronics Nowadays, there are available devices for the simulation of nearly every physical phenomenon. These simulate sensations like forces, temperature, smell, tactile sensation and others for the human being. They will be covered in chapter 2. They comprise tactile feedback systems, including force feedback and thermal feedback [23] [8]. Their development is the domain of engineers to a large extent.

Also for sensing physical phenomenons, technical devices exist, for example temperature sensors and electronic noses [31].

1.5 An Introductory Example

In order to clarify the aim of this work, a first example is given. We compare slips of paper with digital slips. By using augmented reality technology also hybrid forms of slips can be realized, where parts of a slip are physical and other parts are digital. Due to differences between the single slip types, some major questions will arise that will be analyzed later in this work. The CRC card application in chapter 6 that was implemented for this work is related to this example, because it also deals with information written on pieces of paper.

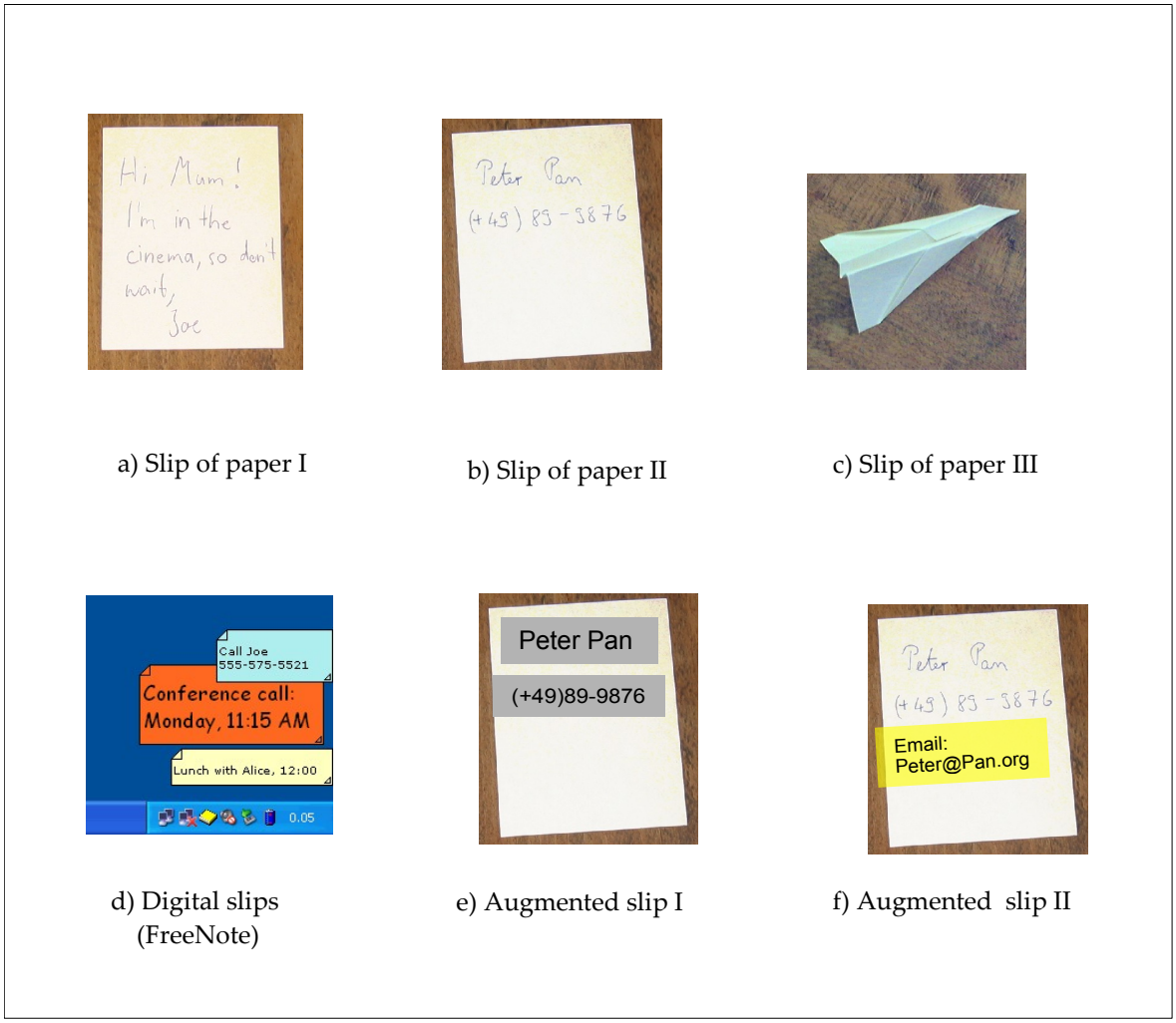
Slips of paper: In their daily life, most people deal with slips of paper (see figure 1.4a–c). We write down things for later use. The slips are used for different kind of purposes. They help us to remind a name or an address. Sometimes we sketch a little drawing. They can also be used as a shopping list. We can even take a slip as a medium to pass information to somebody, for example a phone number. Even more we can take it as a medium of communication by leaving a slip at a place where the target person can read it.

Digital slips: There exist some computer programs that imitate slips of paper on the PC. Figure 1.4d shows such a digital slip. We can put the digital slips on the background of our computer screen. Some of these programs may allow to set an alarm in case the slip is used as a reminder.

Comparison of physical and digital slips: We can see that the digital strips differ considerably from the physical ones. First of all, there is to mention that the digital slips in this example are very restricted in their use, because they were designed for a more specific task. In our example the purpose for the slips is to take textual information. For instance, drawings may not be possible. The physical slips are not so strictly bound to certain context. We could even make a little paper airplane out of the slip, what is probably not possible with any of the software slips.

In order to fulfill the different purposes of a slip of paper in a digital environment, different applications are necessary. For example, when we want to pass a phone number to somebody, a short message to the persons mobile phone could be a good digital substitute for the slip of paper. For sketching some graphic a simple paint program would be appropriate.

On the other side, the digital slips also have some advantages. As the information is in electronic form we can easily use it in other applications by copying it. An address could be transferred to an electronic address book. A reminder could give an acoustic signal at some point of time. Also editing or overwriting the text of a digital slip is easier. Some software might allow to change the color of the slip.



a) Slip of paper I

b) Slip of paper II

c) Slip of paper III

d) Digital slips (FreeNote)

e) Augmented slip I

f) Augmented slip II

Figure 1.4: Different kinds of slips of paper

Mixed slips: By using augmented reality technology, we could think of an application that uses both digital and physical elements (See figure 1.4e–f). Let us assume that we have a video projector that can display digital slips or parts of it directly at the desktop or at the physical slips of paper. We permit purely physical, purely digital, and mixed slips at the desktop. The mixed slips shall be slips of paper that can contain handwritten text or handmade graphics, as well as projected text and graphics from the computer.

Advantages and disadvantages of mixed slips: At first sight, the mixed slips seem to inherit the disadvantages of both worlds. We can not handover a physical slip that contains digital information to another person, because the digital parts are not visible to him. Neither can we copy the entire content. Additionally, we must face in problems recognizing the physical parts and overlaying it with digital parts.

But again we can also find positive aspects. For example, we might already have information

that is partially digital and partially physical. Augmented reality can combine the digital and physical parts so that both worlds combined represent a more complete set of information. We have the freedom of choice when we want to create a piece of information. When the computer is shut off, we can simply use a physical slip.

Advantages can be achieved also when only one type of mixed slips is permitted, one where the paper is physical and all content digital. Then, we have the advantage of having all information digital, and we have still the feeling of presence of a "real" slip of paper, which is very important sometimes.

First Findings: We could see that slips of paper — and more general physical objects — differ considerably from digital slips — and digital objects respectively. Every form has its advantages and disadvantages. Mixed worlds have to cope with that differences. However, they also enable the integration of the digital with the physical world and, even more, they permit the creation of new hybrid objects with interesting new characteristics.

We will now try to analyze the aspects of physicality and digitality in a systematic way. Based on that, we can think about ways of creating and integrating mixed objects.

2 Identifying, Measuring, and Simulating Characteristics of Physical objects

Augmented reality deals with digital and physical objects. If a digital object is somewhere in a space and has no connection to a physical object, this is not an augmentation. The essential idea is to link it with the real world in some form. Therefore, it should be known, which characteristics or properties should be linked with each other. Before this can be done, all the different characteristics — the physical and the digital ones — have to be clarified.

First, the physical attributes and ways to measure them will be described. Such attributes of an object include form, mass, gravity, temperature and many more. Furthermore, it will be analyzed if and how physical attributes can be applied to or simulated for digital objects. For example, an object's position in a space can be stored in some form, and in case the object is visible, it should be displayed at this position; other physical characteristics can hardly be simulated fully by a digital object, for example a certain material. A material's look could be simulated in form of a digital bitmap texture. However, what about the hundreds of other characteristics of a material like heat conductivity, electric capacity, hardness, or deformation parameters? Not all physics can or need to be modeled for a digital objects. The difficulty is not only in storing data of a digital object but also in making them accessible to the user. In augmented reality the focus often is on visualizing digital objects. That is why ways are explored, how to make a certain characteristic visible to the user. But also human senses other than viewing are explored, for example tactile feeling or hearing of digital objects. One question to be answered is, for example, how a user could feel the temperature of a digital object.

Before simulating them, the typical attributes of physical objects are to be analyzed. As its name already implies, a physical object can be described by its physical properties. It must be kept in mind that, for the computer, any physical information is only accessible by sensors. The reality model is fed with the data from these sensors. Usually, sensors deliver imprecise, delayed, or erroneous data. They might also completely fail to provide data. That is why problems due to insufficient sensor data are addressed, which leads to an unreliable reality model.

For each analyzed physical characteristic, possibilities will be shown how to simulate these for digital objects so that the human beings can interact with them.

2.1 Position and Orientation

Position: The first characteristic of a real object we will think about is its location in space. Usually, it is defined by a set of three values that represent coordinates in a coordinate system. Therefore, a coordinate system has to be defined with an origin and three axes (see

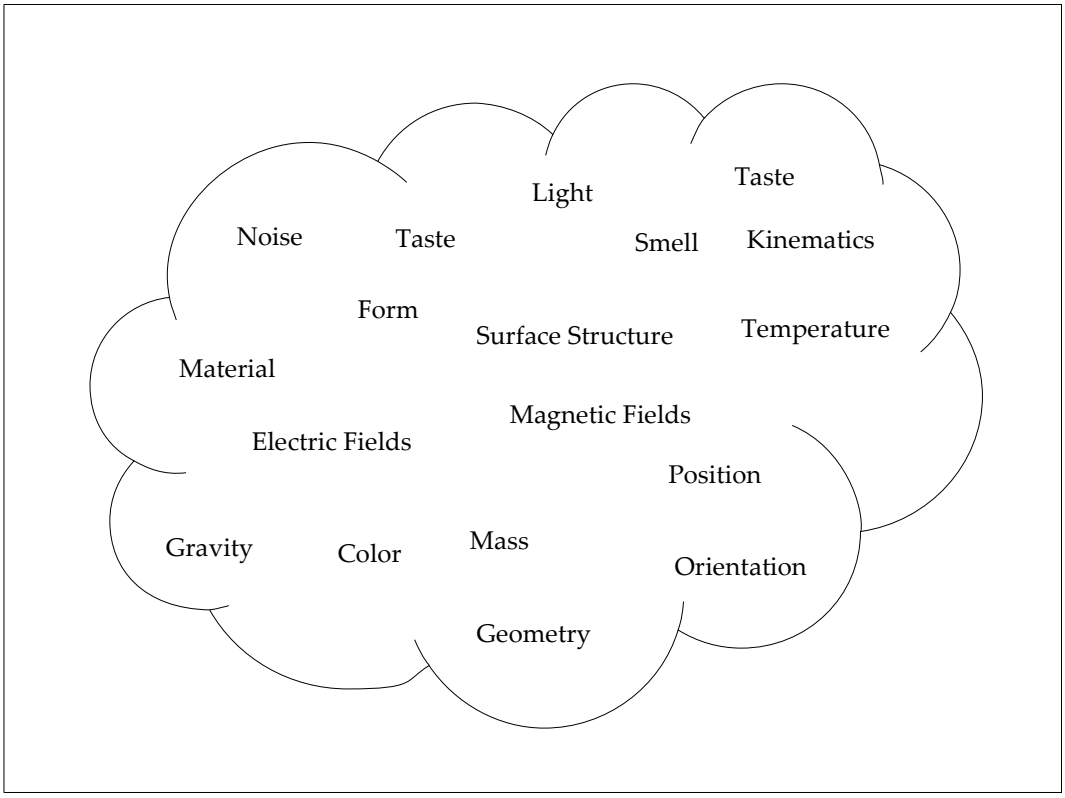


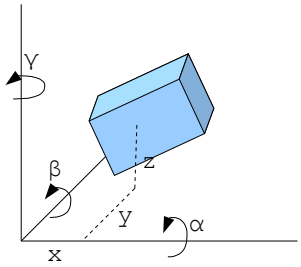
Figure 2.1: Overview of physical characteristics

figure 2.2a). Furthermore, a point of the real object has to be chosen to represent its position. Such a point could be the geometrical center of the object, or the center of mass, a corner of the object or any other point, even if it is located outside the object. The position is represented by three coordinates.

Orientation: The next important aspect is the orientation of the physical object. There are different forms of representations. Either three angles can describe it or a rotation matrix. Figure 2.2b–c show these notations together with values for the position.

Tracking position and orientation: Determining the position and/or orientation of an object in real–time and identifying the object is often referred to as tracking. Often, not the physical object itself is tracked, but rather markers that are attached to the surface of the object (see figure 2.3a and [3]) or bound to it in a different way (see figure 2.3b and [2]). The object's position relative to the marker can be found in the reality model of the physical object.

In today's augmented reality applications, the tracked position and orientation of an object is often the only information of physical world that is directly accessible by sensors. Further information on the object, like form or color, is usually provided by the reality model and not by the tracking system. For the latter ones, the physical object has to be analyzed only



a) Object in a coordinate system

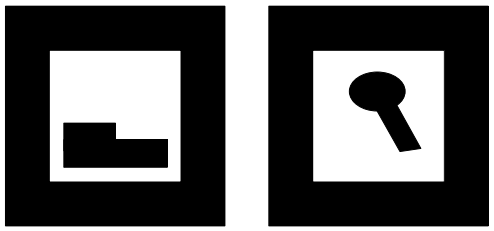
$$\begin{pmatrix} x \\ y \\ z \\ \alpha \\ \beta \\ \gamma \end{pmatrix}$$

b) Representation of position and orientation (I)

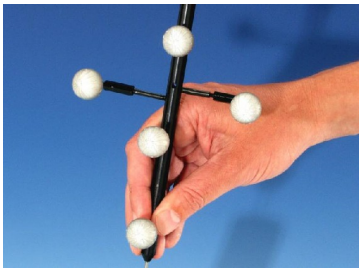
$$\begin{pmatrix} a & b & c & x \\ d & e & f & y \\ g & h & i & z \end{pmatrix}$$

c) Representation of position and orientation (II)

Figure 2.2: Describing position and orientation of an object



a) Markers for the ARToolkit



b) Markers for the A.R.T. system

Figure 2.3: Markers for different tracking systems

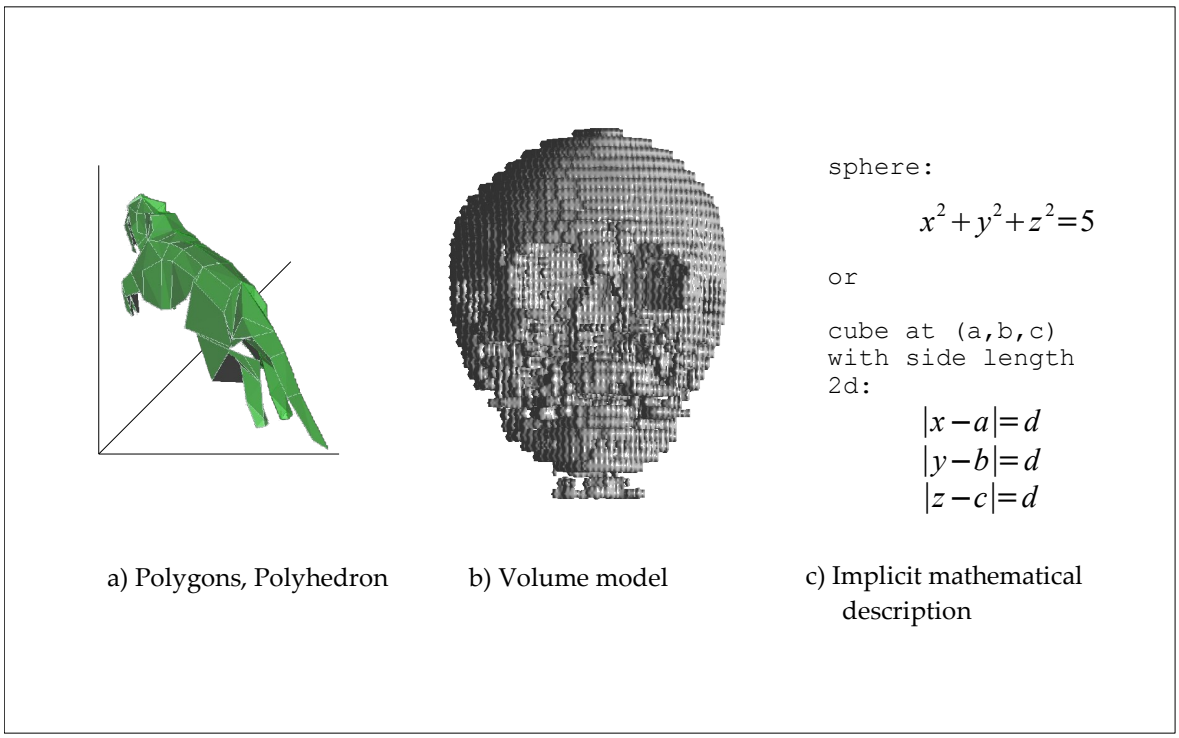
once to get the needed data. Often, data other than position and orientation are assumed to be constant or at least to follow some rule, as we have seen in the tennis ball example in section 1.3.3. If the object does not behave as expected, however, the reality model delivers incorrect information on the physical objects, which may cause unwanted side effects.

2.2 Form

Another characteristic of a physical object is its form, its geometry.

Tracking geometry: Usually, the not whole form of a 3D object can be seen by a human being. Internal geometrical structures, for example holes, are not visible if the material is not transparent. Also the back side of an object can not be seen. For the reality model this means that in most cases an object's form can not be permanently and fully tracked, however. At least parts of the geometric structures can be seen and detected by camera systems. These parts can be matched with known geometries. In that way, physical objects can be identified. Often the form of an object is not constant over time. Elastic, soft or liquid materials can easily change their form, what makes a recognition very difficult.

Representation of 3–dimensional forms: There exist a variety of techniques in order to describe a form in the reality model. A very popular representation is the description with polygons (see figure 2.4a). The surface of a 3D object is is based on points in space. Usually, three or four points form a polygon, which build up the surface. Another way is to assemble an object using basic shapes, such as quads or spheres (b). A disadvantage of both method is that it can not describe some forms exactly, for example an ellipsoid. If it is desired, a description in analytical form is used. In this way, the a mathematical equations and inequations specify the geometry (c).

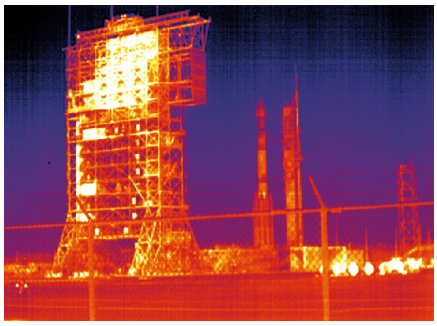


a) Polygons, Polyhedron b) Volume model c) Implicit mathematical description

Figure 2.4: Description of geometries

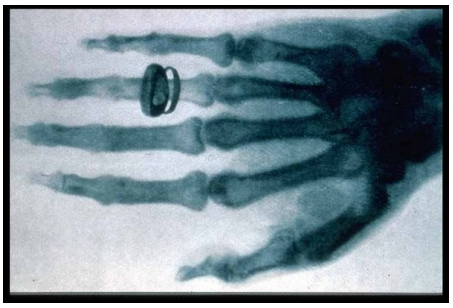
Alternative media of detecting forms: It should be mentioned that visible light is not the only way to detect a geometrical shape. There are also other image formation techniques using the infrared or ultraviolet spectrum of light or other kind of beams like x–rays, sound waves, or water waves (see figure 2.5).

a) Light



b) Infrared

c) Ultrasonic



d) X-ray

Figure 2.5: Various sources for imaging acquisition

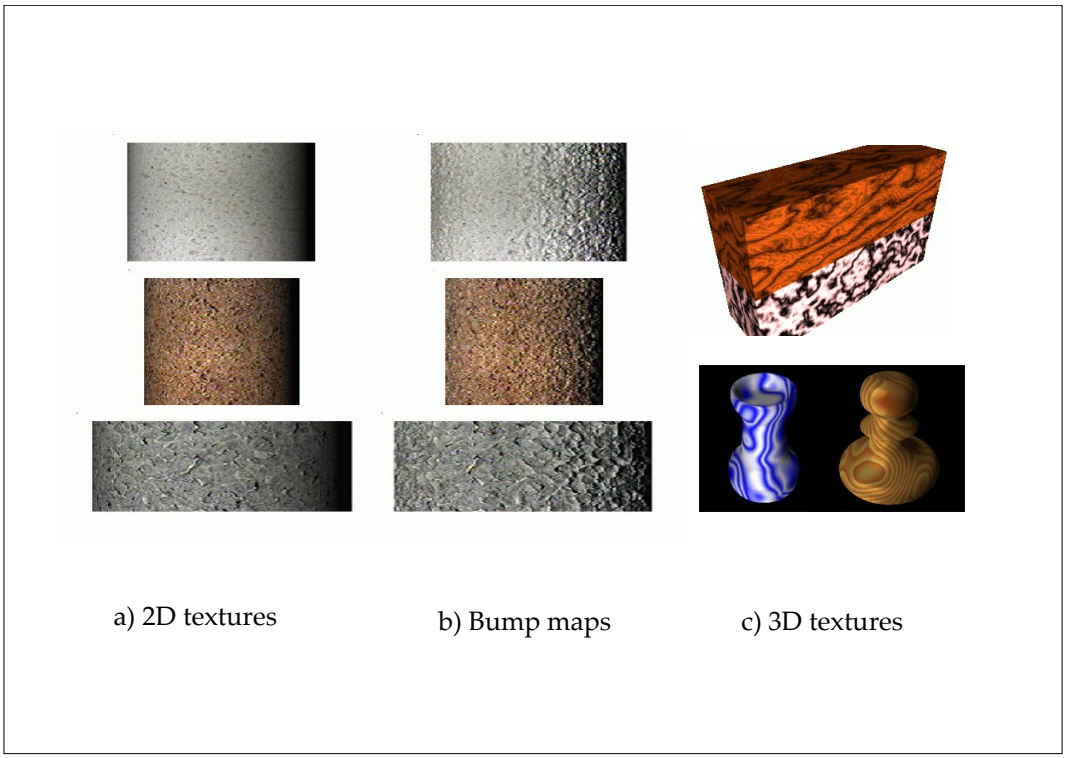
2.3 Material

The material a physical object consists of defines much of its physical characteristics like density (and thus weight), hardness, stiffness, or heat conduction, heat capacity and so on.

This also has implications on its behavior. The characteristics of a certain material can be measured for a specific object. If the material constants are previously known, however, an object's characteristics can also be computed from these constants and its the object's form.

In general, objects consist of more than one part. They can be of different kinds of materials or inhomogeneous materials. Again, a reality model can only be an approximation of parts of the physical world. Because of that, not all characteristics of a material and not all inhomogeneities and details of a real object are available for the reality model.

Visual simulation of materials: For a digital object, a graphical simulation of its material can be made using texture bitmaps. An object's surface can be tiled with the bitmaps, so that a user sees a bitmap instead of a unicolored surface (see figure 2.6a). Whereas 2D–textures can be used for homogeneous materials like metals, 3D–textures are 3–dimensional structures and are preferable for structures that have an internal orientation. Wood is such an example (2.6b). It can look very different depending on the angle, which the surface makes with the wood fibers. Using a 3D–texture, a digital object looks as if it was cut out of a piece of wood. A more realistic view can be created using a more sophisticated physical visualization model. This also includes a realistic lighting model that uses ray–tracing, for example. A Bump–map is kind of texture that simulates 3–dimensional surface structures of an object (2.6c).



a) 2D textures b) Bump maps c) 3D textures

Figure 2.6: Textures

Tactile simulation of materials A material has not only a visual appearance. A material can also be perceived by touching it. We can differ between certain materials by feeling them. However, not only the material is important for the tactile impression, but also form, mass, surface, structure of the objects, and temperature. That is why the tactile sense will be covered in a separate section.

2.4 Color and Light

Complexity of a physical color: Sometimes, the material itself is of secondary importance and only the material's color – thus the object's color – is relevant. However, the color does not solely depend on the material, but also on the light conditions of the environment. Because of that, it is not so easy to find the "real" color of a physical object. It is not even clear what the real color should be. First, it has to be defined what kind of light sources are used, where they are located, and where the positions of the tracking system and the user are. This position can be important, because the color of an object can depend on the angle that it is being viewed. And this applies not only to exotic new materials like car lacquer that seems to have different color when looked at from different angles, but also any kind of reflective material.

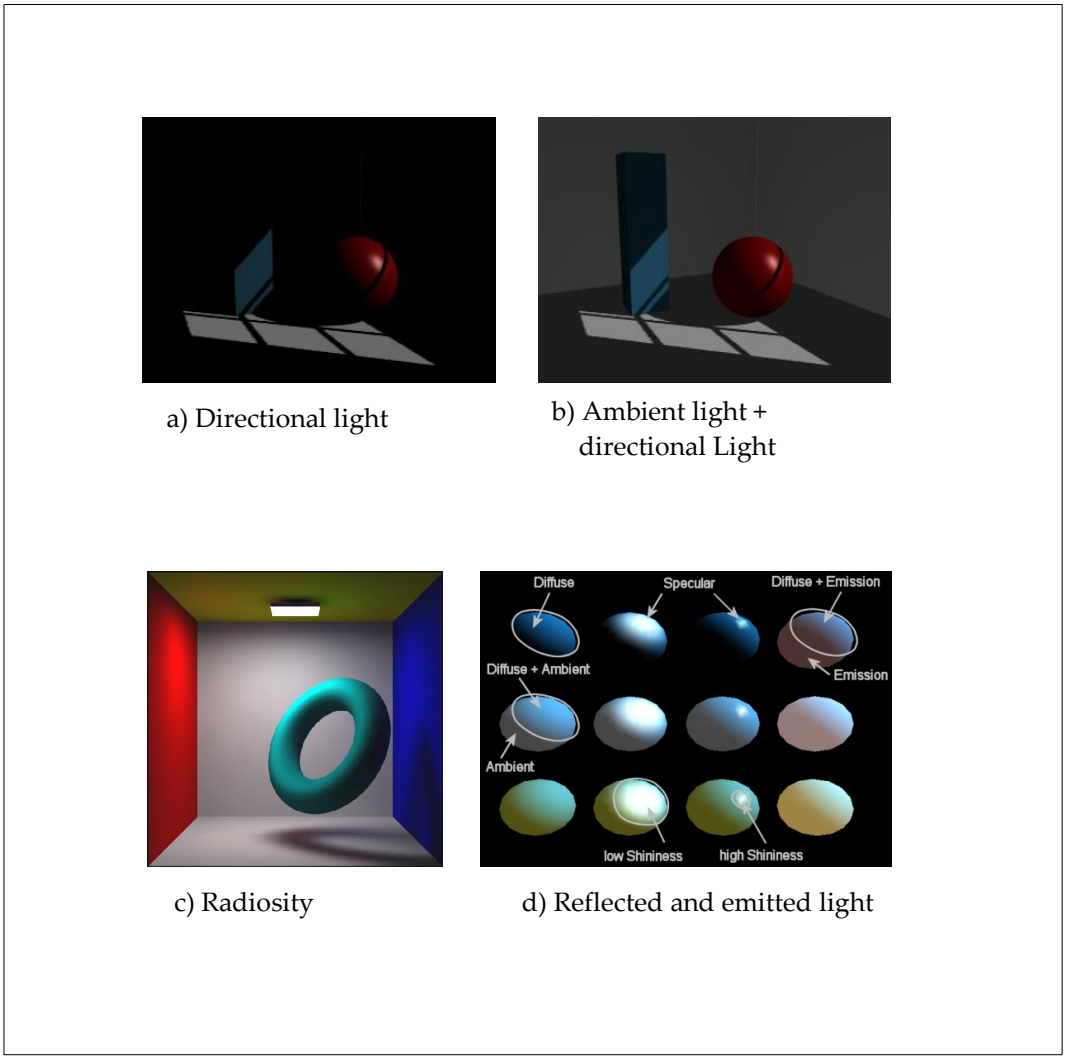
Lighting models: We have already indicated that lighting can be rather complex. An illuminated physical scene is influenced by a lot of optical effects like diffusion, diffraction, and refraction. These are responsible, among others, for transparency and mirroring of objects. All this makes a reliable image recognition a challenging task. For the generation of a realistic lighting in a digital scene, these effects have also to be simulated.

Figure 2.7 demonstrates some of the lighting effects on digital objects. Figure 2.7a shows a scene in directional light. It happens that parts of the objects remain completely dark, because reflection is not modeled. This can be solved by adding a constant background light that illuminates everything, usually called ambient light (b). Reflections can also be computed. Depending on the material, this reflexion can be more specular or more diffuse (c).

All the just mentioned lighting models rely on ray tracing. A different physical illumination method radiosity. It is based on the principle of energy conservation or, more exactly, thermal radiation. For every surface and equation on the absorbed and emitted amount of light is set up whose solution defines its brightness. Radiosity gives a warmer tone to a scene and can better simulate diffuse reflection whereas specular reflection can not be computed. However, both ray tracing and radiosity can be combined.

2.5 Temperature

Measuring temperature: All physical objects have a temperature or a temperature distribution. The temperature of an object could be measured at some points using thermometers and a physical model could calculate the temperature distribution of the reality model for



a) Directional light

b) Ambient light + directional Light

c) Radiosity

d) Reflected and emitted light

Figure 2.7: Lighting models

the whole or parts of the physical object. Possibly just the temperature of the surface is important. Sometimes, it might even be sufficient to simulate just the temperature of the parts of the surface a user is watching or touching. Another possibility of gaining information on temperature is to detect heat radiation. This can be done, for example, by using an infrared camera. The infrared images a camera delivers give information on the temperature of the displayed surfaces.

Simulation of temperature: As temperature is an important source of information about our environment, we could realize it also for digital objects. However, this is not so easy to realize. In case the user really wants to feel the digital temperature as a real temperature, he needs a physical placeholder that has the desired temperature. Its temperature might be regulated with a thermostat. The placeholder could be controlled so that it has the temper-

ature of a digital object. Another possibility is to assign the current temperature of a digital location defined by a pointing device to the placeholder. In both versions the visualization of the digital object and its temperature are separated, which is not very intuitive.

A solution to that problem is to merge pointing device with the tempered object. This can be realized with a tracked data glove that has an integrated temperable surface. There are already commercial gloves available such as in figure 2.8. A deeper insight in the theory of the human perception of temperature and in using it for virtual reality is given in "reference to Thermal feedback model for virtual reality".

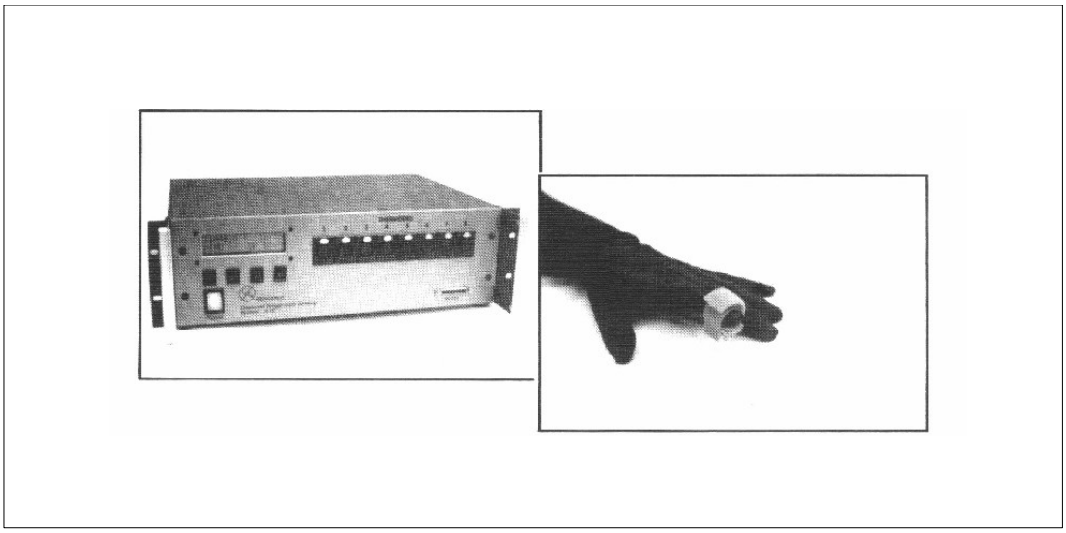


Figure 2.8: Machine to simulate temperature at a finger tip

Visualization of temperature: Often in augmented reality applications, the temperature is not visually reproduced as temperature. Human beings can usually comprehend a temperature distribution better when they can see it than when they feel it with the skin. In order to achieve that, the temperature spectrum is transformed into visible spectra, for example a brightness or color spectrum. The visualization uses the new spectrum replacing or overlaying the natural object brightness or color. This can be seen in figure 2.9. The question is how to model the digital object. Should it store this data as temperature or color? Or both? A clear decision can not be given. The one or the other or both can be favorable in different situations. The three following examples suggest different representations.

- Let us first assume that we have a digital quad that displays the temperature of a physical object by using a color code. The quad needs to access the temperature of the digital object and calculate its color. However, it does not need to have a temperature of its own. Therefore, just having a color is sufficient.

- The situation is different in the second example. We have a digital object with a sophisticated model of its temperature distribution. Also changes in this distribution are simulated. The object is displayed in colors representing its temperature distribution.

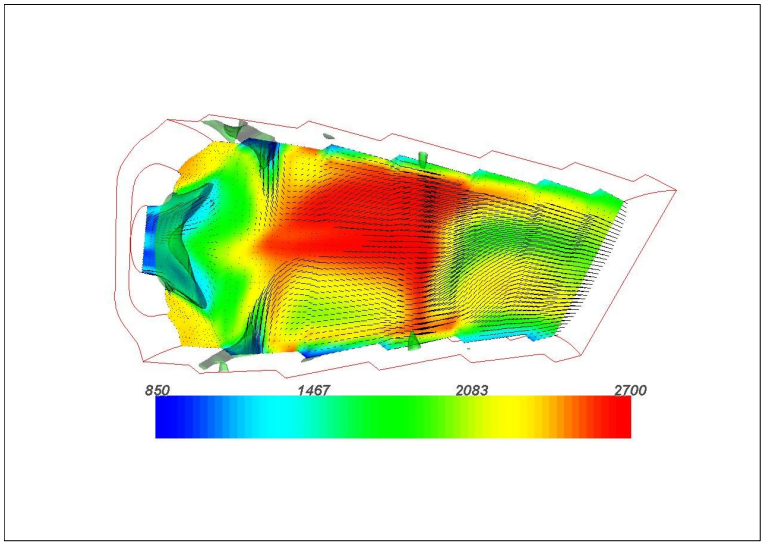


Figure 2.9: Visualiztation of a temperature distribution

In contrast to the previous example the digital object must know its temperature in order to simulate it. Also the color of the object has to be known in order to be able to display it.

- In the last example we assume to have a digital world with a temperature model as described in the previous example. Furthermore, the user can modify the views of the digital world in order to see different visualizations of different spectra of the temperature. As the visualization of temperature is not directly related to a specific object but rather on the setting of the view, it is conceptually better to calculate the color in the view and not in the single objects.

2.6 Tactile Perception of Physical Objects

Senses other than seeing: So far we have more closely looked upon physical characteristics and how they can be measured. Now let us change the point of view to a more human centric one. We can only get information on the world by using our sense organs. The five most important sense organs that we use to experience the world are the following: the eyes are needed for viewing, the ears for hearing, the nose for smelling, the tongue for tasting and the skin for feeling.

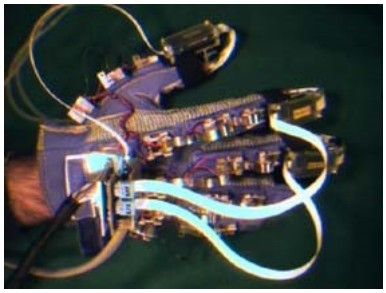
Most characteristics we have discussed so far can be perceived best by our visual sense. This happens, because the human being is a creature that perceives most information through his eyes. In the following sections however, we will try to focus more on characteristics that can be perceived with senses other than the visual one.

Different forms of tactile sensation: We have already talked about the temperature of digital objects. The mentioned methods for feeling temperature with a data glove is one

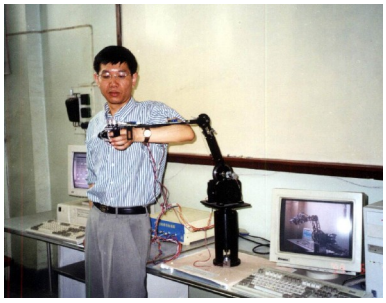
possibility of perceiving tactile sensations.

Other aspects of tactile sensation enable us to feel the form of an object or to feel the surface textures of certain materials. Both can be traced back to the feeling of pressure differences, for example on our fingertips. In case of the former one we feel large–scale differences of pressure. For the feeling of surfaces, in contrast, small variances enable us to perceive a material's micro–structure.

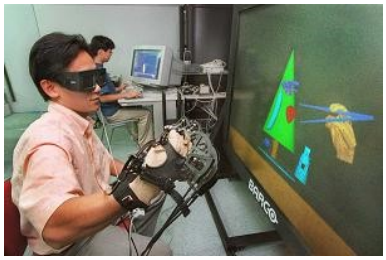
Some research groups work on developing simulating tactile sensations that give force feedback, when a user physically interacts with digital objects. Figure 2.10 shows such kinds of systems (from [8], [23], and [24]).

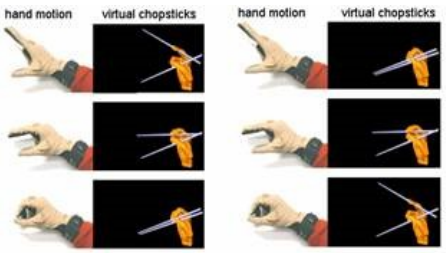


a) Thermal and force feedback for fingers



b) Force feedback for hand movements





c) Tactile feedback for digital chop sticks

Figure 2.10: Systems for tactile feedback

2.7 Mass and Gravity

Though already mentioned in the topics on form and material, we want to have a closer look at the mass of a physical object. The mass of a physical object and especially its implications on inertia and gravity has influence on its statics and dynamics. If some object is put on a table it usually remains there. If it is released somewhere it falls to the ground. If an object has to reach a certain speed, it needs to be accelerated.

In the reality model, a mass can be simulated in different levels of detail. A simple model could just assign a scalar value for its mass, which is located at the objects center of mass. In that way basic kinematics can be reproduced, like simple acceleration of objects, or object collisions. More sophisticated models could provide a homogeneous or even more realistic distribution of mass. By providing that, also the moment of torque can be modeled. In that way also rotations and changes in angular velocity can be reconstructed.

Gravity for digital objects can be simulated in the computer. It is imitated graphically in realistic computer games, for example. Often however, gravity is intentionally ignored for digital objects. Instead digital objects can be positioned to any desired location. So it is possible to have flying or hovering objects that do not underlie gravity. In order to make gravity sensible to the user, the techniques mentioned for tactile simulation can be used. The force feedback systems shown in figures x and y could be used for simulating gravity for digital objects.

2.8 Further Characteristics of Physical Objects: Smell, Taste, Noise

Next to the two senses of viewing and feeling, man has three further senses with which to experience the real world: smelling, tasting and hearing. Using them, he can perceive smell, taste, and noise from his environment.

Noise: Let us start with the sense of hearing. Some objects can emit sounds to their environment. Others generate noise when they hit other objects.

We can integrate sounds into the reality model. Whereas measuring the volume of a sound and recording it can be performed easily with the help of a microphone, its interpretation is much more difficult. This is similar to the sense of seeing: an image can be recorded easily, but the recognition of geometrical forms and, finally, objects is challenging. Correspondingly, sound recognition can contribute to the model of the real world as does image recognition to it. For instance, it can deliver information on material, as different materials sound different. When a sound can be identified as a language, speech recognition techniques could decode the spoken works or even its content.

The sound of digital objects can be simulated by speakers. In most applications, a natural noise from physical objects is recorded. When a certain event happens, for example a collision, a sound is played. A different approach would be to simulate the physical process of noise creation for digital objects. However, this is quite difficult and probably no augmented reality or virtual reality application implemented this so far.

Due to the fact that we have two ears, we can also roughly hear the position where a noise comes from. In order to simulate that, various techniques have been developed like stereo, DOLBY surround sound, THX and so on (see figure 2.11).

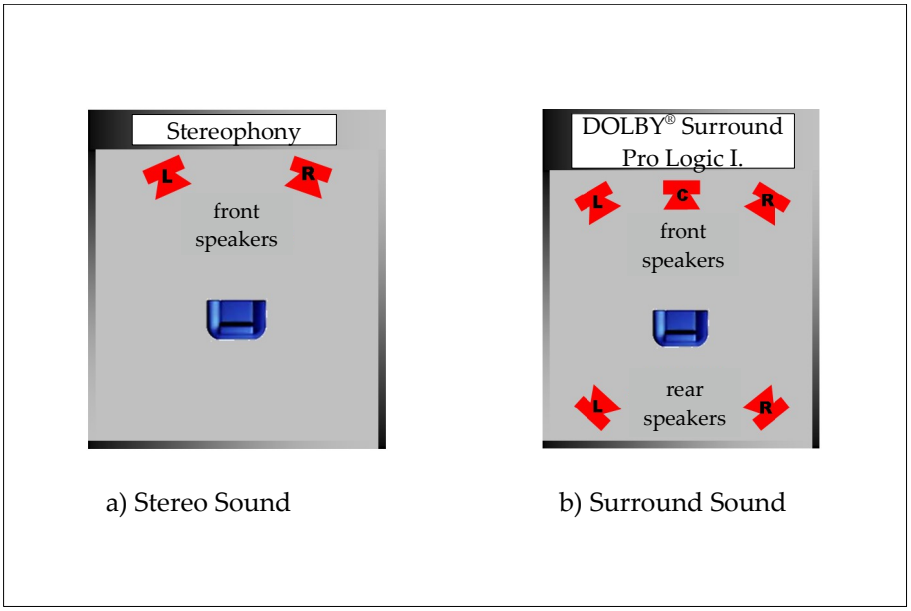
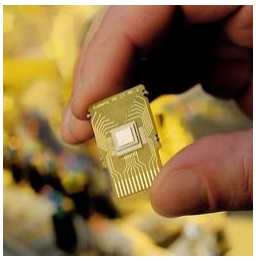


Figure 2.11: Typical sound reproduction techniques

Smell and taste: We will now briefly discuss the two remaining human senses. Smell is generated by molecules in the air that touch receptors in our nose. For tasting molecules touch sensitive parts of our tongue.

Smell and taste can be measure electronically to a certain degree. An electronic nose can perceive smell by constantly analyzing the concentration of certain molecules in the air. Figure 2.12 shows a smell sensor from [53] and an electronic nose system from [31]. They are primarily used for monitoring of air pollution, for example. However, human impression of a certain smell can hardly be measured without directly consulting a person. It is same with taste. A chemical analysis can deliver information on a substance, but how it actually tastes can not be fully predicted.

At the moment, both characteristics do not play a significant role in augmented reality applications. Some industries, however, are interested in creating artificial smells, for example the perfume industry. Furthermore, shopping malls create a kind of augmented smell reality by giving off scents that increase the desire to buy something. In the field of simulating taste, the food processing industry interested. In this way, cheap food can be made to taste like more expensive quality food. In the future, an augmented menu in a restaurant could enable us to see and taste certain dishes before ordering them.



a) Sensor for detecting and analyzing odor

b) Electronic nose

Figure 2.12: Electronic registration of smell

2.9 Other Physical Forces and Their Impact

Now we want to shortly mention other characteristics of physical objects by looking at further physical forces that act on physical objects. Next to the recently covered gravity, there are electro–static and magnetic forces and the effects they have on bodies are – among others – friction, deforming processes.

Electro–static forces are responsible for a lot of effects in our world. This does not only apply for large scale electric fields, but also for molecular or atomic dimensions. They are responsible for the fact that we usually cannot move objects into each other, because the electric fields of the atoms do not permit that. Eventually, electric fields are also responsible for deformation processes, elasticity, and friction. In the following we will shortly discuss the named points.

Friction makes physical objects slow down, or at least it makes them accelerate more slowly. The energy spent for this is usually converted to heat. In the reality model a physical object can be given a friction factor so that friction can be computed. It should be mentioned that in order to simulate friction at least a simple kinematic model with gravity has to be provided.

Deforming processes can also be simulated. Materials and engineering science are interested in computing such processes. There exist a variety of sometimes very specialized simulation software.

There are two main difficulties, though. The first one is that a deformation is often a chaotic process so that a result is not predictable sometimes. The other issue is that the calculation of a deformation can be very time intensive so that for many situations an adequate simulation can not be calculated in real–time. So it can not be used in augmented reality or virtual reality applications.

Breaking of objects: The same is valid for the fracture of physical objects. Suppose we have a cup made of porcelain that breaks because it falls on the floor. It is not completely predictable, where it breaks and in how many parts. However, a previous analysis of the porcelain may indicate some irregularities, where the cup probably breaks. Digital objects are often objects with idealized characteristics. This idealization causes problems, when physical effects should be simulated. A digital teacup could therefore break into completely symmetric pieces, what seems to be unrealistic for the user.

Frequently ignored forces: Next to electric properties, physical objects can also have magnetic properties. Furthermore, there are a variety of other forces that can mostly be explained by electromagnetic effects, such as Van der Waals forces, capillary forces and many more. Under some (often extreme) conditions they can have a noticeable influence on physical objects. However, there are by far to many effects to discuss them all here. For most augmented reality applications, they are of minor importance and, hence, they are neglected in this work.

Difficulties in measuring forces: One problem with most of these forces here is the fact that they can only be monitored with some difficulties. There are not so many techniques available that allow scanning an electro–static or magnetic field of a piece of space in real–time. In comparison, cameras are very cheap and effective providing visual information. That is why the trajectory of an object that is influenced by electric or magnetic forces my not be retraced by the reality model. Also electric current that flows in physical objects can hardy be captured externally without any electronic measuring device attached to it.

We have seen that there are a lot of physical forces. If a physical object reacts on some force, it is often difficult to find out which effect was responsible for it. The human being often does not have special organs for sensing these forces or their effects. He needs measuring devices in order to build a physically correct reality model. For augmented reality applications, however, it is unrealistic, impractical, and also often unnecessary to measure all these forces and effects of all physical objects involved. However, the physical objects can behave in an unforeseen manner due to these forces. Furthermore, digital objects can not access these forces and are therefore excluded from these real world effects. Even if some of these forces are simulated for all digital objects by using the aforementioned force–feedback systems, there remains a barrier that handicaps a seamless interaction between physical and digital objects.

These difficulties impose restrictions when physical objects are to be integrated with digital objects in order to build mixed objects, what is covered in chapter 4.

2.10 Limitations of the Reality Model

Augmented reality software always refers to the reality model as if is was the physical world. However, the reality model — as its name already says — is just a model and has its limitations. We have already seen some of this limitations in the discussion on physical properties. Some of them are inherent, so that they can not be solved even by an advanced reality model.

One limitation results from the fact that all data from the reality are based on sensor data. Sensors have a certain accuracy. Beyond that accuracy all data are approximations. Even with an extremely high accuracy some results are not predictable because a process can be chaotic. That means that even if the accuracy is increased and increased, the result of a calculation will always change and never converge to a stable value.

Another limitation of the reality model is that not all objects can always be tracked. If a tracked object suddenly disappears, it is rarely the case that it physically disappears, but instead it is not tracked any more.

A challenge in tracking is the unique identification of objects. Maybe the tracking system is not able to differ between certain very similar objects. For example, it is not possible to identify all visible nails in a box full of nails. However, every nail is unique, even if we can not make a difference. As long as there is no difference at all, we can cope with the problem, as the objects are replaceable.

A tracking system gets serious problems if it finds one of two very similar objects, because it can not identify it. Maybe its uniqueness is not visible from distance, but from near or from a different perspective the difference becomes evident. If the assignment to the object was wrong the reality model is erroneous. We will come across this problem another time, when we cover mixed objects. Then, some solutions to that problem will be given.

2.11 Summary of physical characteristics

We have now discussed the most important attributes that a physical object can have. Several possibilities were addressed that showed how to model these characteristics for physical objects and how to measure them. Also possibilities were shown how to simulate these characteristics for users of digital environments. Table 2.1 gives a summery. Please note that the table combines different concepts. Some characteristics are more focused on physical measurability (for example “position”, “form”), others are more focused on human perception of the physical world (for example “hear”, “smell”). The table also contains overlapping. A model on “kinematics”, for example, requires “mass”.

It seems unrealistic to imitate all digital characteristics in one application. On the other hand, the question is not only whether it is possible to simulate them all in a perfect way, but also if it is necessary or desired. Sometimes it could even be dangerous, if a user can not differ between simulated and physical objects, for example, in medical augmented reality. We will have a further discussion on this topic in chapter 4, when we have gained a deeper insight on digital characteristics and characteristics of mixed objects.

Physical characteristic	Quantitative description [unit, if applicable]	Example(s) for measuring	Examples for simulating characteristic on digital objects
Position	Three coordinates [mm]	Tracking with camera; magnetic tracking	Display object at the proposed position
Orientation	Three angles [°], rotation matrix	Tracking with camera; gyroscope	Display object with proposed orientation
Form/ geometry	Description with polygons, base volumes... [list of positions points, edges, surfaces and volumes]	Edge detection, other sorts of feature detection	Display geometries, for example using OpenGL
Material	Many different material constants	Chemical analysis, image recognition, recognizing sound of material	Textures
Color	Different color formats [RGB, YUV ...], transparency	Color from camera image	Display color
Light	Brightness, light distribution	From camera image	Lighting models like raytracing, radiosity
Temperature	One value [°C, °F], more sophisticated for temperature distributions	Using Thermometer; infrared camera	Termal feedback
Tactile percept.	Mixture of feeling temperature and pressure		Force feedback systems
Mass	One value [kg]	Weighing	Force feedback systems
Electric fields			Force feedback systems
Smell	Amount of certain molecules in the air	Electronic nose	Create synthetic smell
Taste	Amount of certain molecules in substances	Electronic tongue?	Create from gustatory substance
Noise	Amplitudes for superimposition of basic sinus waves [dezibel]	Recording with microphones	Sound synthesis; play recorded sounds over speakers

Table 2.1: Summary of physical characteristics

3 Special Characteristics of Digital Objects

Up to now, we showed how to transfer the characteristics of physical objects to digital objects. We have only seen what properties physical objects provide and we tried to understand them, measure them, analyze them, and tried to transfer them into the digital world. The mathematical models of the characteristics can be used for digital objects, so that they simulate the physical characteristics. Also the possibility of "rematerializing" the characteristics have been evaluated, for example force feedback systems that can make digital objects touchable. Now we want to see it the other way around and search for aspects that can be found in digital objects and that their physical counterparts do not possess originally.

In order to find such new aspects, especially those who do not exist for physical objects, we will also look for concepts that have been developed in software engineering and other fields of computer sciences. They make behave digital objects in a way that is not possible for physical objects. For example, concepts like creation and duplication are much easier to realize for digital objects than for physical objects. Access rights is another concept that can be used for digital objects. Only authorized users could be able to modify a digital object. This is different for physical objects. Imagine a room that is accessible to anyone that contains some artifacts. Whether somebody has the right to modify an object is often more a legal issue. A person could ignore this and, for example, destroy or take away something. This is generally easier compared to the knowledge and the effort that a computer hacker needs in order to circumvent access rights.

The key point is that a computer is a freely programmable device. Everything that is describable by an algorithm can be realized in the digital world of the computer. With respect to digital objects, all their properties can be freely defined by the programmer, even if they do not exist or do not make sense for physical objects. For example, there are mathematical models of geometric objects that do not exist – at least in our everyday world. Imagine a cube with four dimensions in space, called a hypercube.

The space for digital solutions and thus for characteristics of digital objects is unlimited, even uncountable. Therefore, it is not possible to find a complete set of characteristics of digital objects and it is difficult to categorize them. In the following, we will discuss some characteristics of digital objects as they can be found in typical augmented reality applications. We do not speak of objects in general as they are used in the sense of object oriented programming. Usually, we think of digital objects that have a visual representation, so that they can be displayed to the user and be used for augmentations. Examples are basic geometric forms like cubes or spheres, information labels, or any more complex structure composed by the simpler ones.

When we discuss characteristics that digital objects in augmented reality could have, we will also search for solutions that have been made in traditional window applications. A lot of ideas have been tried to be realized for classic windowing systems, far more than those we

use in our everyday work (see [51] and [46]). Some might prove their advantages better in augmented reality than they did in traditional 2D windowing systems.

3.1 Possibilities of Visual Manipulation

First, let us explore which possibilities there are for a digital object to be manipulated visually. As stated in the introduction, the possibilities of digital manipulation are uncountable. Anything could happen. An object could grow until infinity or change its form, split itself in two parts or reunite. The same object could be displayed twice identically or with different aspects and so on. We well pick out some possibilities.

3.1.1 Visibility

One basic characteristic of a digital object is, whether it is visible or not. The possibility to switch digital objects off and on sounds so trivial. However, it should be made clear that this characteristic is a fundamental difference to physical objects. The user usually expects that an invisible object that he could see before and that finally disappeared, is not at its place any more. However, it could also be that the object is still there and manipulatable, just with the difference that it cannot be seen anymore. Maybe one could touch it with a force feedback glove as described in the previous chapter.

3.1.2 Transparency

There is not only visibility and invisibility, as there is not only black and white. A digital object can also be displayed with different grades of transparency. So there is no necessity to limit a digital object to the extreme states of visible and invisible. This can be advantageous. Transparency can enable us to see hidden objects (see figure 3.1a). Furthermore, a complex structure like the famous bottle in figure 3.1b can be visualized better.

Furthermore, the interaction could depend on the grade of transparency. A little example should illustrate that. There shall be a digital cube in space and a force feedback system as mentioned in chapter 2. The freely manipulatable degree of transparency could reflect the shift in interaction as following: if the transparency is more than 50%, no interaction should be possible (see figure 3.1c). A user's hand can go through the cube without any physical resistance. If the transparency is 0%, the digital cube should feel like a solid cube. For transparencies between 0% and 50% we could imagine a soft transition between these extereme states. At 30% transparency, for example, the user's hand could still go through the cube, but he feels some resistance that also moves the object.

In the case of head–mounted see–trough displays (see figure 3.2b and c), digital objects always have a certain transparency, especially if the environmental light is very bright. Furthermore, the transparency can strongly vary depending to the external light conditions. In using this this technology for visualizing digital data, slightly different grades of transparency should not reflect different kinds of interaction.

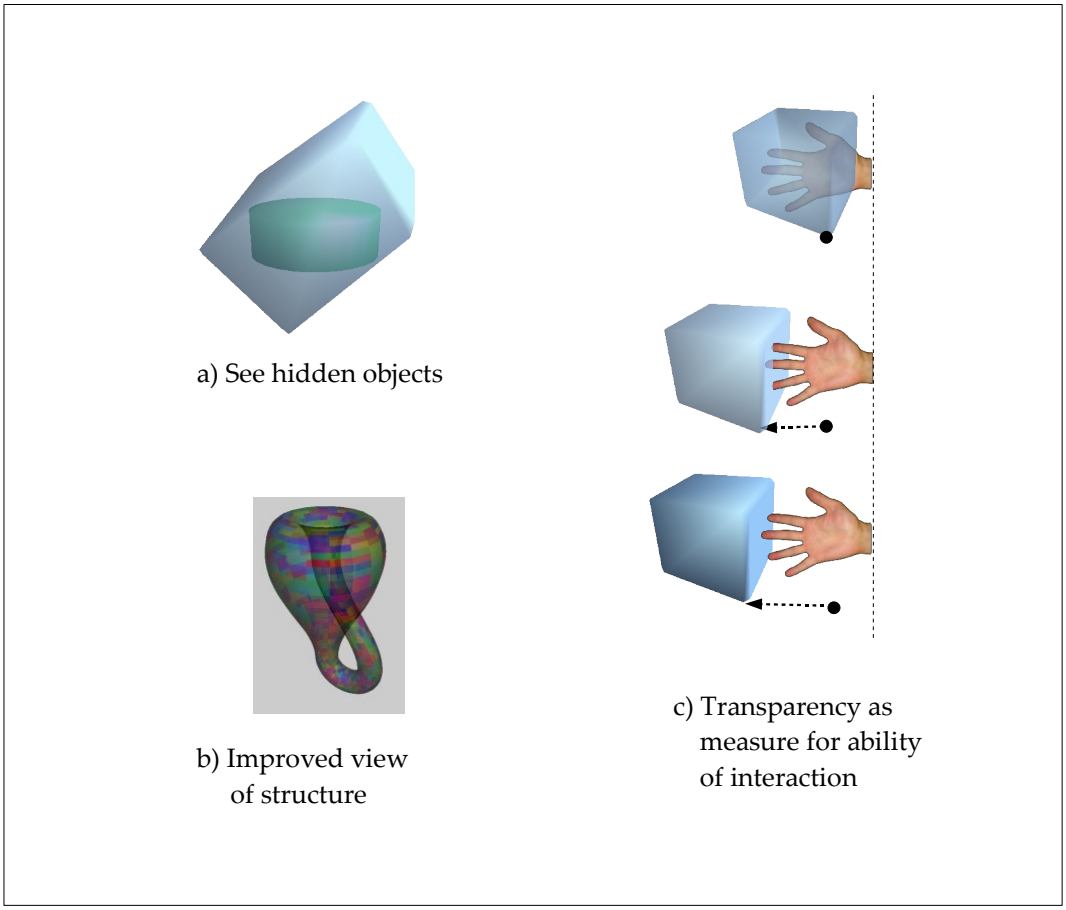


Figure 3.1: Using transparency for digital objects

3.1.3 Different Views

Next, let us shortly talk about another powerful idea of displaying digital objects. We could display the same object more than once. The object can have the same appearance, we could see the same object from different points of view, or the object could be shown with different aspects visualized. For example, an additional infrared view could give information on the temperature of some objects, like the rocket in figure 2.5. When the object changes, all views of the object can be updated. The object could be manipulated directly, for example with a keyboard. It could let you increase or re–enter the position of a digital object. Often, however, the data of an object are not manipulated directly, but instead the user interacts with the visualization, for example, he picks it by clicking with the mouse and moves it to a new position. The possibilities of interaction that a visualization provides is usually realized in a so–called controller. An input is noticed by the controller, who modifies the object. This very typical separation of the object, its visualizations, and controllers is called model–view–controller pattern (see figure 3.3). It is widely used in software engineering. More information can be found in the design patter book of Gamma [22].

Of course it would also be possible to visualize different states of an objects. The object could

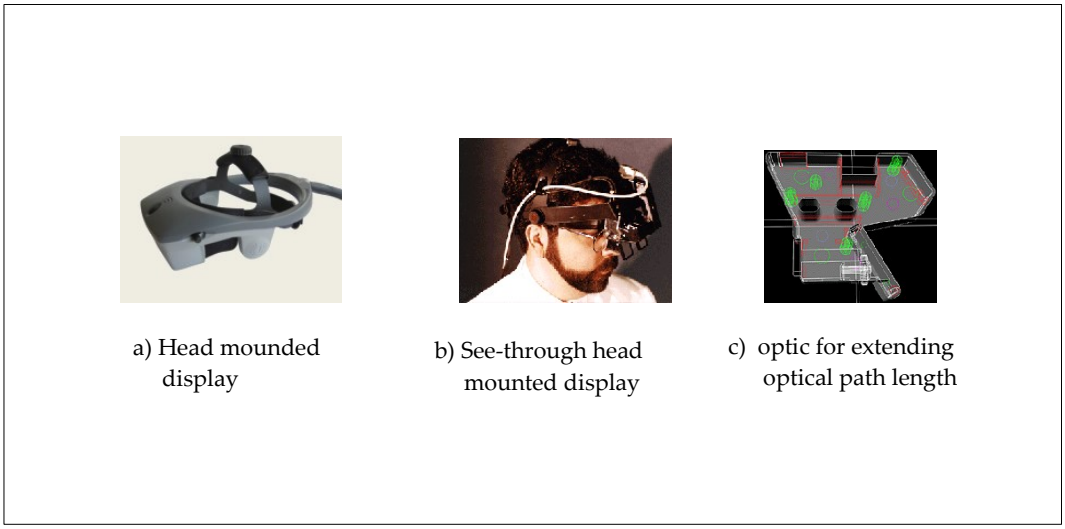


Figure 3.2: Transparency in head–up displays

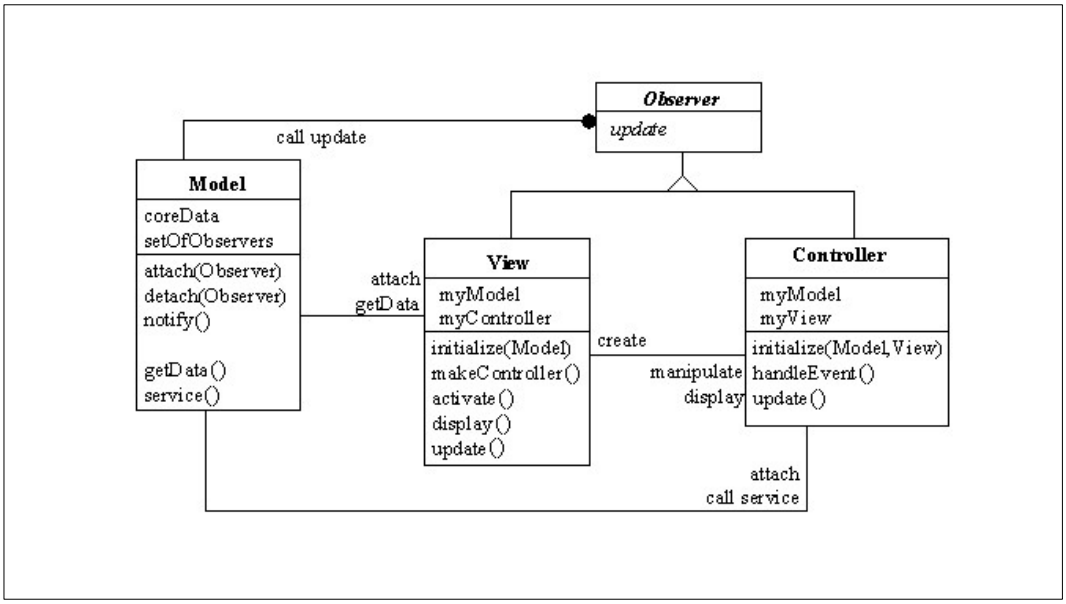
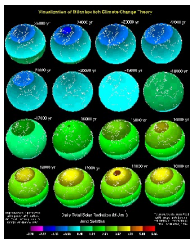
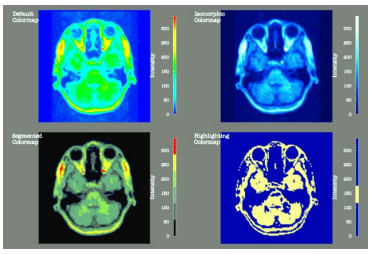


Figure 3.3: Model view controller pattern for enabling different views for one object

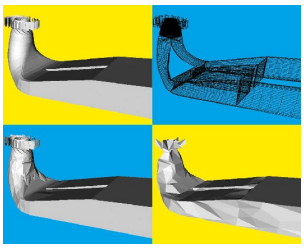
be visualized in different colors (see figure 3.4b) or in different rendering quality (c). Maybe even completely different aspects are displayed (d). Furthermore, it could be interesting to see how a digital object evolved over time by displaying the initial and the final state at the same time (see figure 3.4a). Another useful application of the visualization of several states of an object is to show both as it is now and how it would look like if a certain change would be applied. In graphical manipulation programs a certain image modification procedure can often be seen as a preview. If the effect is not as it is desired, the procedure is not applied.



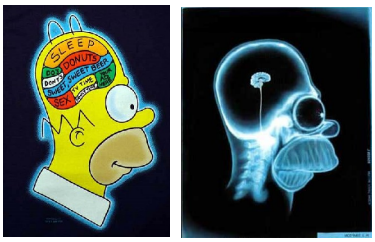
a) Visualization of change over time



b) Visualization with different colors



c) Visualization with different rendering quality



d) Visualization of different aspects

Figure 3.4: Multiple forms of visualization of the same object

Visual information is the most important channel of information for human beings: that is why we are also called visual beings. In visualizing digital objects, not only information that human beings usually sense with their eyes can be displayed. Also data of invisible physical information can be made visible. This includes temperature, deformations, forces like tension, pressure, magnetism. We already mentioned several techniques in chapter 2.

3.1.4 Geometric Transformations

Now, we want to discuss some geometric transformations. In comparison to physical objects, digital objects allow far more kinds of transformation in space. Any mathematical function that maps the three coordinates of space on three new coordinates can be applied to an object (see figure 3.5b). Digital objects are freely movable to any position in space. For example,

they can be enlarged if the user wants to see more details (3.5a), or be shrunk. For certain applications also other transformations may be applied.

It may happen that objects entirely or partly hide other objects. For physical objects this may be a problem. In order to see the hidden objects either the objects or the users have to change their position. For digital objects, different kinds of solution can be thought of. Objects in the foreground could be made transparent so that the hidden parts can be seen. Or important textual information of hidden objects be moved into the foreground or to a different position (see figure 3.5c).

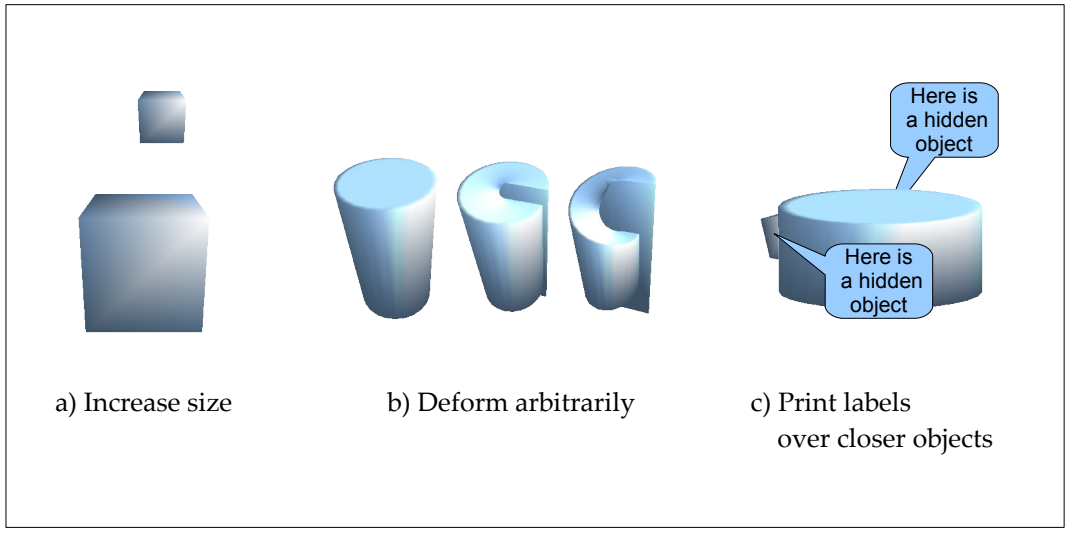


Figure 3.5: Visualization of overlapping objects

Another form of manipulation is the consistent change of objects with identical or similar characteristics. For example, we could perform a task like: "turn all red objects into green objects" or "move all little objects that are linked to object a $35cm$ into direction y. In doing so, we can define ways of comfortably manipulating groups of digital objects, as it is not possible for physical objects.

3.2 Pseudo–Physical and Unphysical Behavior of Digital Objects

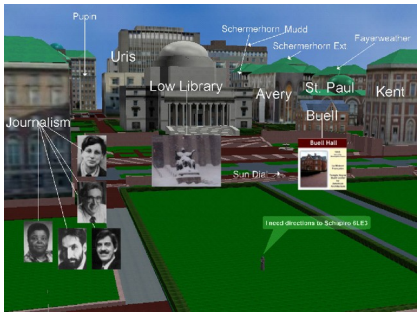
When we evaluated the characteristics of physical objects we already discussed how these characteristics can be simulated for digital objects. Now we want to give a few examples, where digital objects intentionally do not underlie these physics or where they use own rules that define something like their own kind of physics.

No gravity: In general, digital objects do not underlie any gravity. In our daily work with the PC this is very advantageous. Just imagine the scenario that all windows would fall down on the screen, or the boxes drawn on an electronic presentation slide would glide down to the bottom of the slide. Instead digital objects can remain at the very position they

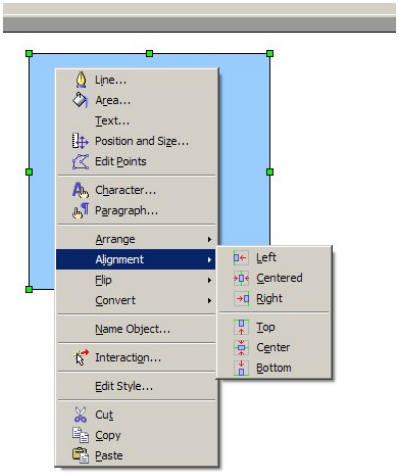
were once put at. In augmented reality scenarios, objects can stick at a fixed position, where they hover no matter what happens. Other objects could be fixed regarding the users view. So they will never be out of sight and always at the positions the user expects it.

Pseudo–forces: Sometimes, however, forces that apply to digital objects are advantageous. This is not necessarily gravity. Often these forces are developed specifically for software applications so that they support the users work.

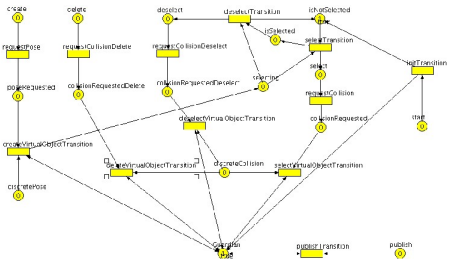
Forces can be used in order to align digital objects with others (see figure 3.6a); other algorithms hinder the objects form overlapping each other (3.6b). Most users will also know the effect that objects are snapping to a line. If an object comes close to such a line, it is attracted, so that the boarder of the object finally touches the line. Vector based drawing or construction programs as well as typical presentation programs use this technique.



a) Avoid overlapping



b) Alignment of objects with snap-in



c) Self-organizing Petri-net

Figure 3.6: Pseudo–forces for digital objects

There exist also more sophisticated positioning algorithms that make objects reorganize automatically. So elastic bands can be created, that digital objects, which have a connection,

do not move away to far from each other. The opposite are forces that hinder objects from being too near or even overlap each other. There are windowing systems that automatically rearrange windows when they overlap. Another example is a program that organizes graph structures. The program "Renew" performs this task for Petri–nets created with "jfern". It implements both attraction and repulsion of objects. It makes the nodes move away if they are too near and move together if they are too far away.

Object permeation: We just mentioned the term "overlapping". For 3–dimensional objects that are viewed by somebody, overlapping is not clearly defined. Digital objects can either overlap by sharing some space volume or just overlap in the user's view, so that one object is in front of the other. We already covered the latter in the topic on possibilities on visual manipulation (see section 3.1). Here, we will address the former type of overlapping. What is usually not possible for solid–state physical objects, happens automatically for digital objects: they permeate each other without any resistance. If a permeation of objects is not wanted, collision detection is to be done and a method is to be chosen that avoids a permeation. This can be an elastic or an inelastic collision, with or without deformation or a non–physical event like the recently mentioned snapping of objects. In case this is allowed, the question is, how to model the interfering parts. Depending on characteristics that the digital objects have, characteristics of the permeating parts have to be defined. Should the color of one or the other object define or dominate the overlap? Should the color be computed from the overlapping objects' color and, if so, how? Or should there be a special highlighting color for the overlap? What about simulated characteristics like density? Should the overlap have the sum of densities of the overlapping objects or better the average? All these elements need to be decided in case of permeating 3–dimensional objects.

3.3 Uniqueness of Digital Objects

Unlike physical objects, it is possible to uniquely identify digital objects. Usually, a digital object is stored in a computer's memory. The address in the computer's memory where the object description starts, could therefore be used for identifying the object. As two objects can not be stored at the same location, every object has a unique address. The reality is not so easy, however. Objects could be relocated, so that an identification might fail. A pointer that is updated in case of a relocation could resolve this. We still get into difficulties if the object lives in a distributed environment where more than one computer is working. We can not definitely decide whether two objects that are living on two computers are unique or whether they only contain the same values. In order to solve this, a concept referred to as unique object identifier (OID) or digital object identifier (DOI) can be used (see [26]). It is used for managing intellectual property.

First unique IDs: One well–known and very successful example for is the ISBN number that is used for books that are published. These numbers are not identifiers for a single book but for an edition of a book. That is why it is not exactly an ID for a physical object. One approach for realizing digital object identifiers were done by database developers. They introduced OIDs for distributed databases in order to maintain consistency.

URIs and URLs: Worldwide unique IDs for digital resources were made popular by the internet in the form unified resource locators in short URLs. Also an Email–address is a kind of unique identifier for an electronic post box. The URIs are used rather for static content of resources. And in the case of URLs they are bound to a location rather than an object. When an object, for example a web site, moves to a different location the URI also changes.

UUID: For having a identifier that is also unique for all times, the DCE — a subgroup of the ISO–Organization — created a standard called "Universal Unique IDentifier" (UUID) [45]. An object's UUID is a 128 bit number, computed from the hardware address (MAC) of the computer that creates the object, a time stamp, and some randomized function. It can be used, for example, in databases or for remote procedure calls like CORBA.

Consequences of uniqueness: Digital uniqueness seems to be very simple, just an additional attribute of a digital objects. Its consequences for the mathematical foundations of the digital world, however, are enormous. In order to build the reality model, a differentiation of identically looking or behaving objects is one of the major concerns. Confusing objects can happen easily and is not always the fault of a bad recognition software but sometimes it is an inherent problem, for example if two objects look exactly the same. Often a confusion of objects is not foreseen and may cause errors that may also lead to the termination of a program. The correction of errors that result from confused objects may be difficult, nondeterministic, or impossible. Even if the visualization and the behavior of two digital objects are identical, even if they are at exactly the same place they can be distinguished by their ID.

3.4 Object Creation

Unlike physical objects, digital objects can be created, destroyed, or copied instantly. A physical object either exists in nature as it is or has to be produced by someone. Natural objects, for example plants, animals, or rocks, can not be created or produced instantly by a human being without any tools or raw materials. Furthermore, some physical objects need a very long time to develop. A stone from the jurassic, for example, is built in thousands of years from dead shells and other sediments. Often such processes can not be sped up considerably. Or they may be difficult to control. Even more, for most of them the user has neither the tools nor the material in order to built it. It is the contrary with digital objects. As long as the application provides and allows the creation of these objects, there is no limit in number. However, this power brings also some problems to solve.

3.4.1 Space for new objects

First of all, the new objects require display space, at least if they have a graphical representation. Of course, digital objects need another form of space as well: memory. However, they do not physically occupy any space when displayed in a virtual reality scenario. At the position we want to put it, there might be another object. Or there is not enough space at the desired position. If overlapping is not allowed, we either have to place it at a near place

elsewhere or the surrounding objects have to be relocated. There are sophisticated methods that enable the dynamic relocation of all affected objects, as we have seen in section 3.2.

Sometimes, the amount of space of the digital world is limited. Then, it can happen that there is not enough space at all in the digital world to place the object to be created. There is a variety of ways how to deal with such a situation (see figure 3.7):

- One possibility is to forbid the object (3.7a), which is not very satisfying.

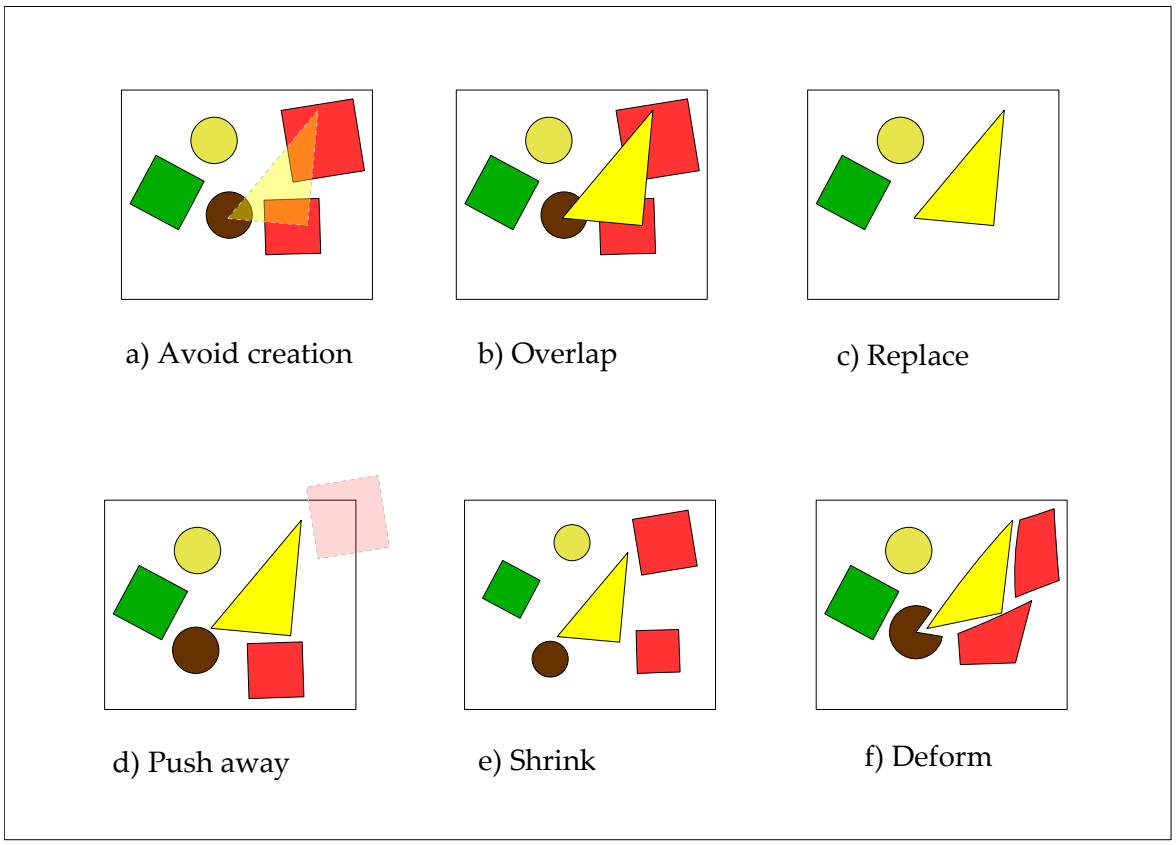


Figure 3.7: Object creation in limited spaces

- Another way is to allow overlapping (3.7b). This is a very common practice in windowing systems, for example.
- In a third version, a new object could replace the hindering objects (3.7c). This can happen in several ways. I want to give two examples how this could happen: the existing objects that overlap with the new object can be removed so that there is space for the new object .
- An alternative is to force the insertion of the new object and move the others away (3.7d). Some objects are pushed outside the boarders of the limited world. We can say that the new object has replaced the displaced objects.

- We are still not at the end of finding solutions for the input of new objects. An idea is to create space for new objects by shrinking all or some of the objects including the new objects (3.7e). This method can also be seen in presentation software like Powerpoint or OpenOffice. You can create text boxes with fixed boarders. If the box is full and you continue to write, the font size is automatically shrank (see figure 3.8).

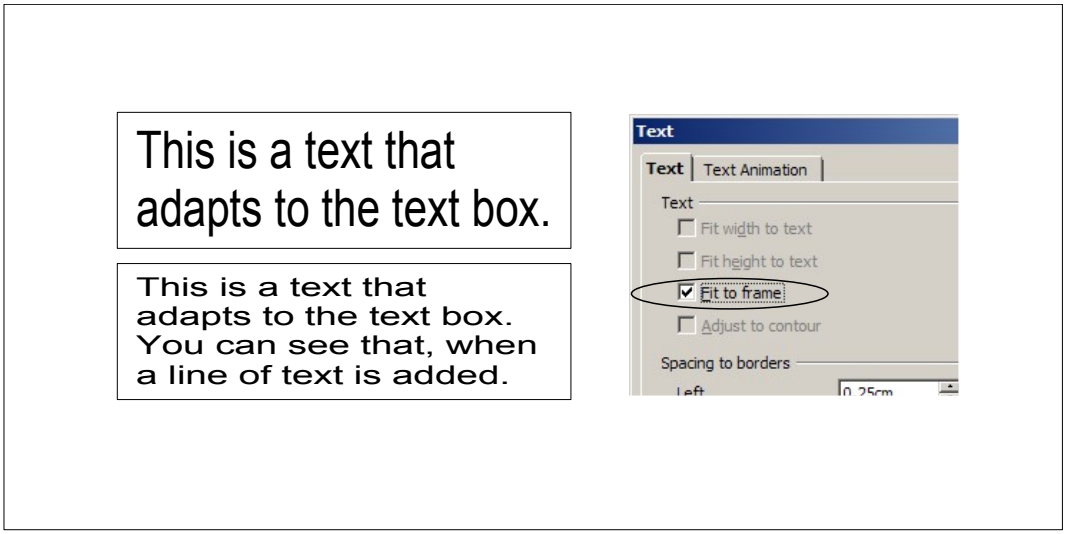


Figure 3.8: Automatic text resize in a word processor

- As the last proposal to mention here, a deformation of the digital objects' shape can be performed in order to create space for the new object (3.7f). Here, we could think of deformations as they happen with physical objects when we try by force to insert something, when there is not enough space.

3.4.2 Violation of Laws due to Object Creation

A problematic issue of creating digital objects is the fact that physical laws, which are simulated for the digital world, might be violated by inserting a new object. For example, if mass is simulated, the conservation of mass is not given, once a new object is introduced into the scene. An electric field, which can be switched on instantly, is also a violation of physical rules. We could accept these kind of violations for the moment of object creation.

Singularities: However, we have to avoid or limit the unwanted effects of such singular events. Let us look at the electric field example in more detail: if electromagnetic interaction is modeled an electric field is switched on instantly, current is induced in surrounding conductive objects (see figure 3.9). The voltage of this current is proportional to the ratio of change of the electric field, i.e. to its derivative. If — due to the insertion of an electrostatic object — this change happens instantly in no time, the derivative of the electric field becomes infinite at this point of time and the digital world could become instable and crash (3.9a,b). It is advisable to ignore the current for this point of time. But in doing so, the current that

would have been induced by the new object is lost. This could be solved by softly raising the electric field of the world (3.9c,d).

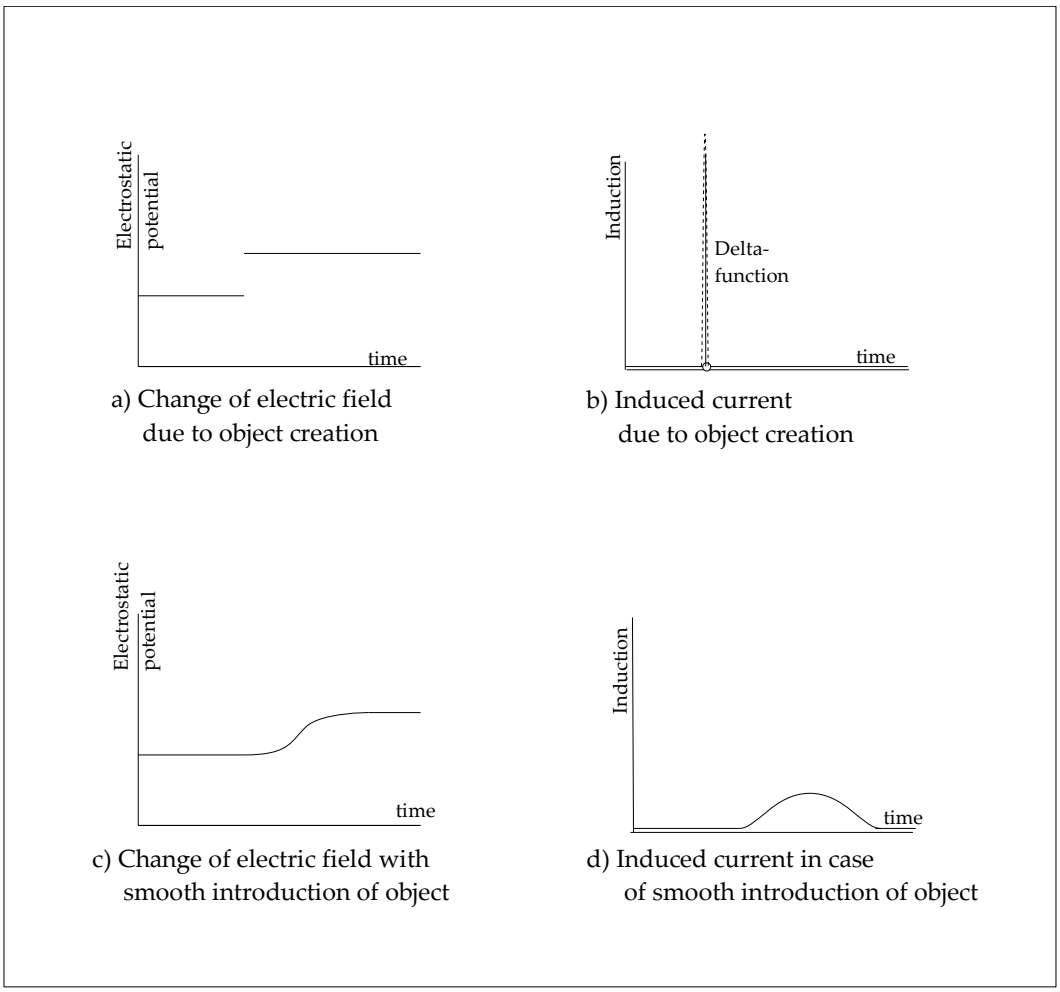


Figure 3.9: Singularities due to object creation

The designers of the digital word has to decide, how to model the insertion and find out how to avoid such problematic singularities in his world.

3.5 Object Deletion

Also deletion of digital objects causes some difficulties that have to be resolved. We just mentioned singular points that occur when an object is removed instantly. In this case, we have to deal with the same difficulties as we did at object creation.

3.5.1 Restoring Actions after Object Deletion

Another question is, in how far we model the deletion as an inversion of object creation. As we have seen, the insertion of a single object can have impact on several other objects. When we delete this object, we have to decide if we want to revert these impact so that we can have something similar to the initial situation. Not all processes that happen during the insertion of an object are reversible, though, because information is lost. Some scenarios would theoretically be reversible for digital objects but may break physical rules that have to be followed. Let me give you two examples:

- Imagine that there are two cubes and we want to create a third cube between the other two (see figure 3.10a–c). The external cubes have to move a bit away from each other in order to have sufficient place. When the middle cube is removed, the ancient status of the remaining cubes can not be restored, because the initial position is not known anymore.

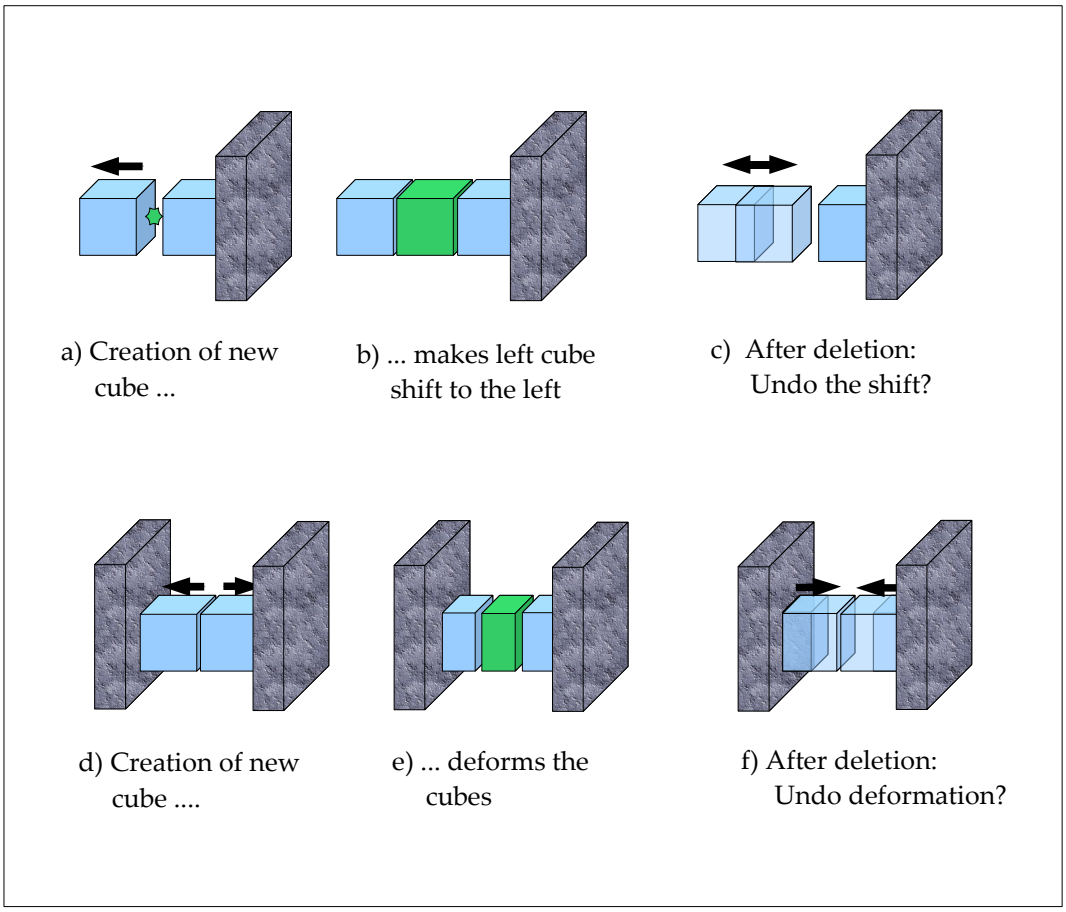


Figure 3.10: Restoring actions after object deletion

- For second example we assume that we have a small boarder around the two cubes so that the two cubes have to be deformed in order to find a place for the new objects (see

figure 3.10d–f). If the new object is removed, we have to decide whether the deformation is to be undone or not. In the case that the objects are not elastic, the deformation is permanent and from the physical point of view it is not possible to invert that process. It is not possible to calculate the original state of the object, because information on that is lost. Elastic objects on the contrary save the information on its original shape in the form of internal tension that makes the object go back in its original form, when external forces disappear.

3.5.2 Collapse after Deletion

It may happen that, due to the deletion of a single object, the digital world collapses. For example, if we have a wall of bricks and we delete a brick, the wall might crash. However, this would also happen if we would simply remove the brick from the wall. In general, we have to avoid that the world collapses unintentionally because of an insertion or deletion. This is sometimes hard to predict, however. If it happens, a kind of saving point is helpful where we can go back to. We will see soon what else the saving of scenes can offer. A collapse often happens if some objects can not live without other ones. When we remove an object that other objects depend on, we have to decide whether the depending objects are also removed, whether they can be bound to alternative objects, or whether the deletion is stopped. We could allow the removal only after the depending ones have been removed.

An example for such a collapse with depending objects is a scenario where a world is modeled including gravity. The objects shall all be positioned on a base plane. When the base plane is removed, all objects would fall down infinitely because nothing would stop them. In this case all objects depend on the base plane to exit.

3.5.3 Deletion of Groups of Objects

We already stated that we can apply sophisticated manipulation methods on certain groups of objects. Also deletion is — though a very extreme — kind of manipulation. This enables us to perform the deletion of groups of objects with identical or similar features. For example, if a digital world is polluted with lots of small particles, which are not needed anymore, they can easily be destroyed.

3.6 Replication of Objects

Is is certainly an advantage of digital world that information can be easily replicated. When dealing with a digital object we can, for example, generate duplicates of it. This can also be seen as a special form of object creation. An object that might have cost much work to produce can be multiplied easily. In section 3.1.3 we already mentioned the advantage of different views of one object. There we assumed to have one object with only the views duplicated.

Basically, we can to differ between forms of replication. Either the copies are still considered as belonging to the same object or they are considered as different entities. If the replicated

objects have to be modified separately, we will choose the latter one. From the point of creation of the copy we will have two objects that behave independently.

As already indicated, replication of objects, works relatively easy for digital objects. In chapter 4 we will try to replicate mixed objects which is far more challenging. There, the different kinds of copying will be covered in more detail.

3.7 Saving, Logging, and Reconstructing Digital Objects

In contrast to the real world, digital worlds can be saved, archived, and continued easily.

3.7.1 Benefits of Saving a Digital World

As first big advantage of saving all or parts of the digital world, the work can be interrupted and continued at any time. Unless other have access to the data, no one can manipulate the world and the world will not change on its own. Another advantage is that the world could be transferred to another computer and continued at another place. Also someone else could continue in interacting with the world. A saved world can also be copied easily, which is not necessarily the case for a complex world of a running system. In that way, several people can work with copies of the world. We should not confuse that with interactive scenarios where people interact together on the same world. We will discuss that later.

We already heard that, under certain conditions, the digital world can run into invalid states or it can collapse. If we have saved a state of the world before that crash, however, we can restore the world. The saving could be done regularly and it could iteratively overwrite old states when the newer ones have proved not to cause such a crash.

The saved worlds can also be used to enable the reconstruction of historical states. The progress of the evolution can be traced back and statistics be made.

3.7.2 Limiting the Stored Data

Not necessarily all data has to be stored, maybe because they are not needed or because the memory that is needed for saving has certain limits. Maybe for some scenarios just the position of the objects is necessary, the speed can be neglected. The objects need to be accelerated, if they should have a certain velocity.

Even entire objects or groups of objects could be ignored while saving. Imagine a fountain modeled with thousands of water particles splashing around. We could just save the fountain with the ability to produce water but without the water particles. When the fountain is saved and the world reloaded later the fountain starts with no water but will immediately start pouring out water as it did before and after a while there will not be any significant difference to the state of the fountain before the saving action.

3.7.3 Logging Information and Its Usefulness

A saving of the whole digital world may cost a lot of resources and can not be done too frequently. However, it could make sense for the user to undo the last interactions he did. In order to realize this, the interaction of the user with the world and relevant changes in the digital world could be logged continuously. When something undesired happens, maybe due to some side–effects, the user could undo the last actions. A lot of authoring software offer undo and redo functionality. This concept is widely and frequently used and should find its way also in augmented reality systems.

3.8 Access Rights and Locking of Objects

We will now describe two well–known features of digital objects that are especially useful for collaborative work, which chapter 5 is about. These comprise the presence of access rights for digital objects and the possibility of locking objects.

Access rights: When several people are working together, we can restrict some people to perform certain things on some objects. Maybe only the creator of an object is allowed to change the position of an object. Or only a very powerful user can create certain new objects. The software concept of access right is known for a very long time and was especially needed in multiuser operating systems and database systems. The concept of groups and roles facilitates the management of access rights. A group is simply a collection of users. A role in this context is a set of permissions that can be assigned to a user. It was developed by database developer to easier manage databases. The advantage is that once you defined a role, it can be assigned to single users or groups of users. In that way not all rules need to be assigned to all users separately. Usually, groups and roles can be defined recursively: a group can be defined as a collection of single users and already existing groups and roles can be defined as a collection of permissions and existing roles.

Locking of objects: For some digital objects it makes sense that only one user at a time interacts with it. For this purpose, the technique of locking can be used. A user that locks a certain object can modify it exclusively. The other users have no permission or only read permission. In the case of such a reading permission several possibilities exist for the state, in which the other users will see the locked object. They could see the object in the state it was locked or in the state it was when they requested the locked file, or they see how the locking user manipulates the object. Which of these possibilities is used depends on the application, and especially on the kind of performed collaboration. When the user has finished his exclusive manipulation, he could make the changes permanent or discard them and unlock the object.

Comparison to physical objects: When we deal with physical objects, access rights are not as easy to realize. They either have to be locked into some room so that only the people who have a key can interact with it. Or you have to realize access right on a legal basis: only certain people are allowed by law to do something, other ones are not. Nonetheless, it is

easily possible to ignore the rules and do forbidden actions. Violating the rules of a digital object is considerably harder, because some computer hacker knowledge is needed in order to break them. Furthermore, for digital objects it is possible to do a strong selection of an object's characteristics regarding access rights. For example, a user could be able to move an object, but he is not allowed to change its orientation.

To some degrees, access rights can be transferred, though. We can refer read access as to viewing an object, write access as to changing it, and executive access as to using it. In order to prohibit to view an object, we could lock it in. In order to "execute" it, but forbid "writing" it, we could construct it in such a manner that using it does not change it. To most such combinations, a solution can be found, however it is also a matter of interpretation how physical rights are realized.

For physical objects, locking does not exist in that form. Private areas can serve this purpose. A document at a person's desktop, for example, can indicate his exclusive claim on working with it. An exclusive use can also be achieved by providing the possibility of making a reservation on a physical object, for example a video projector.

4 Mixed Physical and Digital Objects

So far, we have seen which characteristics physical objects have and how these characteristics can be transferred to purely digital objects. Furthermore, we have also had a close look at digital objects and the digital worlds they form. Many common aspects were discovered, but also different concepts were identified that do not exist in the other world or that are only transferable with limitations.

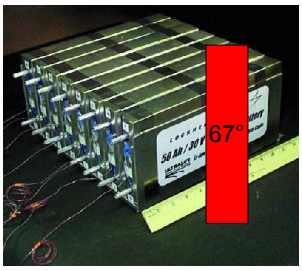
In augmented reality, we make use of enriching physical objects with digital ones. Hence, the physical world is overlaid by a digital world. In order to do that, we need to establish connections between the two worlds. And by doing so, we get new kinds of mixed physical–digital objects with new behaviors. In this chapter we will explain what mixed objects are, how they can be created, and how they behave.

4.1 Defining Mixed Objects

In order to build a mixed object, at least one digital and one physical object are necessary. These two or more objects need to be interconnected in some form. In general, any form of dependency of a digital and a physical object can be seen as a mixed object.

Explanation of mixed objects: Using that definition, also a battery together with a bar indicating its temperature is a mixed object, even if both are independent otherwise (see figure 4.1a). This might seem to be uncommon at first. It can be explained by the fact that the human being usually regards things as one object that are bound together physically in some form. Two things that can move independently are rather seen as two objects. Five chairs are seen as five objects (4.1b), whereas five elements forming a chain are rather considered as one object (4.1c). However, if the chairs are aligned smoothly so that they touch each other, we maybe consider them to be lines of chairs (4.1d). The ability of the human brain to combine single independent but somehow related objects to a so–called chunk is a known phenomenon in psychology. It makes sense, because the human brain can only keep about eight things in mind at the same time and one chunk only counts for one such thing. By grouping several objects into one chunk, complex situations can be overseen more easily.

In the case of the temperature bar, its location is not physically bound to the battery. So we see them as two objects and not as one chunk. However, the position is only one characteristic of an object and there are so many other characteristics that can be linked with each other. Here, we will allow a wider definition: every form of connection of digital with physical objects can be seen as a mixed object.



a) 1 mixed object

b) 6 chairs

c) 1 chain

d) 3 rows of chairs

Figure 4.1: Entities of mixed objects and chunks

Conclusion: We can formulate the connection of a digital with a physical to a mixed object in a simple way. It is an arbitrary function that depends on at least one characteristic of the physical and one characteristic of the digital object.

4.2 Requirements for Mixing Digital and Physical Objects

When we unite digital and physical objects in a mixed world we create mixed objects with new combinations of digital and physical characteristics. However, we have seen an asymmetry of physical and digital characteristics.

4.2.1 Requirements for Digital Objects

In the last chapters, we got the impression that transfer of physical aspects to digital objects is often possible by simulation. Almost all physical aspects like color, mass, inertia, deformation can be simulated to some extent. Whereas the realization of visual and auditive simulation is very common with today computers, all other characteristics like tactile simulation or taste generation are more difficult to establish. For most augmented reality systems, a visual and auditive representation of digital objects is sufficient. Therefore, a realistic physical model and technical devices are necessary like displays and speakers that support the perception of these characteristics for the human beings.

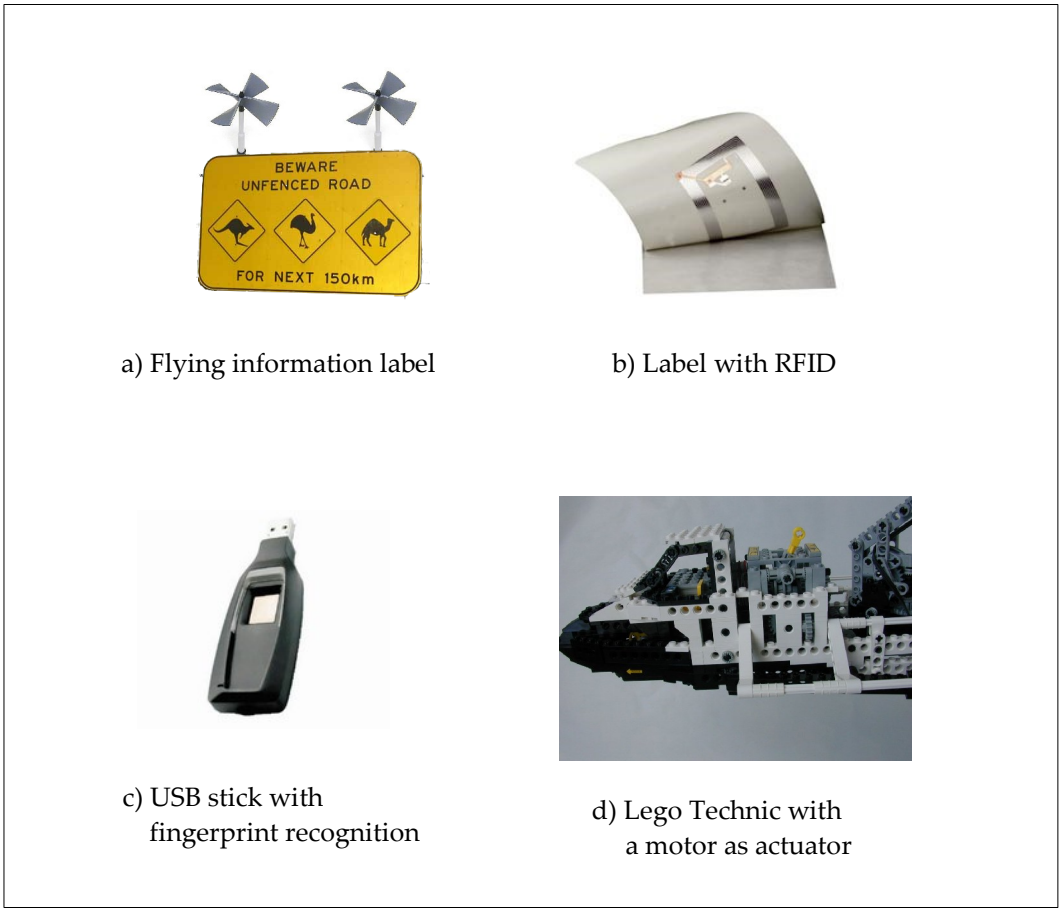
4.2.2 Requirements for Physical Objects

On the other side, the transfer of typical digital characteristics to physical objects often seems to be impossible. To repeat a few of them: access rights are difficult to guarantee, duplication and bilocation are not easy to realize for physical objects. To some degree, the physical world seems to be limited and restricted in the adoption of some digital world concepts. So far, however, we have treated the two worlds differently. We designed digital objects specifically to meet certain characteristics and used special physical devices for them to give feedback to the user. In contrast, we have taken physical objects as they are and we have not tried to design them for a specific use, so that they meet characteristics that are usually required by digital objects. I will give a few examples for such newly designed physical objects. Afterwards, it will become clear why these objects have not yet been mentioned in the chapter on physical characteristics.

- **Flying objects:** Let us take information labels that are frequently used in augmented reality systems in order to provide information on physical objects. Would it not be possible to create small physical information labels with little propellers, so that they can freely fly around, just as digital information labels do (see figure 4.2a)? At first sight this may seem a bit ridiculous. It is so much easier to provide information by sticking the labels somewhere and in case the label is likely to be overseen, it can be illuminated or so. However, with some engineering skills it should be realizable. Maybe, for some applications, it might be the favorite solution.

- **Access rights for physical objects** can be realized to some extent as well (see also 3.8). Fingerprint recognition is available even for small electronic devices and only persons that are authorized can use it (see figure 4.2c). Also other restrictions can be implemented in hardware. A physical object that we can move only on a certain trajectory may be fixed on a kind of rail just like a wagon on a roller coaster. More sophisticated restrictions regarding movements could be controlled by a robot arm that is attached to an object.

- **Trackability:** To some degree, tracking can be seen as an attachment of a digital characteristic. In most cases, objects that are to be tracked have a special design or markers so that they can be recognized by a tracking system. This is a characteristic in an analog form, but designed specifically to provide information that can be used by other digital



a) Flying information label

b) Label with RFID

c) USB stick with fingerprint recognition

d) Lego Technic with a motor as actuator

Figure 4.2: Physical objects with digital characteristics

objects. Sometimes, such as in the case of RFID sensors, the provided information is already present in a digital form that is readable by electronic devices (see figure 4.2b).

- **Controllability:** A further issue that separates the digital and the physical world is the fact that it is difficult to influence physical objects through digital objects. How could a digital object control a physical object? The answer is, again, to design the involved physical objects so that they can interact with the digital ones. Motors could make a physical object move (see figure 4.2d). The information on where to move and how to move could be transmitted to a receiver that the object needs to have.

Consequences for physical objects: Alone the fact that we want to assign digital characteristics to physical objects often leads to the integration of electromechanical and electronic components into the physical object or into the real world. Similarly, the physical realization of digital characteristics demands electromechanical and electronic devices that transfer the digital characteristics into the physical human world. Electronics and increasingly also electromechanics are fields that are in the intersection of the digital and physical world. They deal with the transformation of physical signals, movements and forces into digital signals

and backwards. And they try to find mechanisms for transmitting, processing, and storing digital information on physical components. By adding technical components to a physical object, it also becomes something like a mixed object.

4.2.3 Requirements for Tracking and Visualization Systems

We mentioned that a visual manipulation of a mixed world can be done in a head–mounted display. A digital magnifier could manipulate the real world video picture, so that the appearance of physical objects is changed. In general, such manipulations caused by the interaction of physical and digital objects are very difficult to handle. I want to mention two aspects of such interactions:

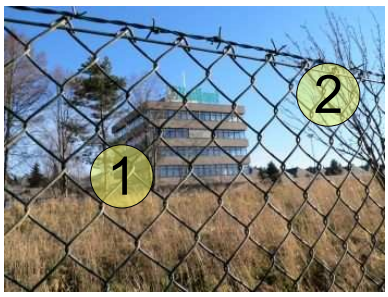
- **Overlapping:** Objects that are closer to us hide objects wholly or partially that are behind them, at least if they are not transparent. In mixed worlds digital objects can overlap physical objects and physical objects can overlap digital objects (see figure 4.3a). In order to do this in a physically realistic way, all physical objects, or at least those who overlap digital objects need to be tracked. Not only their position and orientation needs to be known but also their geometric structure. At least nowadays this is not realistic, so that in most cases digital objects are simply projected over the not–tracked physical objects.

- **Lighting:** Even more difficult to achieve is a consistent lighting model in a mixed world. All light sources of the physical world need to be known in order to illuminate the digital objects correctly (see figure 4.3b). We could also imagine digital light sources. If a digital light source should also be able to illuminate the physical world, all physical objects need to be tracked and their natural appearance be digitally altered according to the digital light (see figure 4.3c).

- **Shadow generation:** Another challenge is the realistic generation of shadows in a digital world. It is sometimes also considered as a part of the lighting model. Three components are needed to create a shadow: a light source and two objects. One object throws a shadow to the other one (see figure 4.3d). Any of them can be either physical or digital, so that we have eight different cases of how a shadow can emerge in a mixed world. For example, a physical object, illuminated by a natural light source, can throw a shadow on a digital object. Or physical object illuminated a digital light source can throw a shadow on a physical object. With the exception of the purely physical case of shadow creation, which is done by nature, and the purely digital one, for which excellent solutions exist, a correct shadowing model is often not implemented in augmented reality.

4.2.4 Limited Physical–Digital Integration

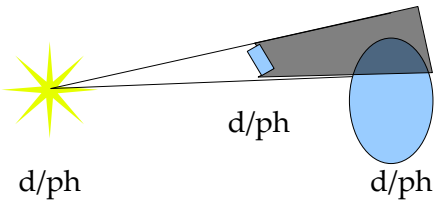
Considering all that, the question arises whether we really have to create such a perfect melting of physical and digital objects. Of course interconnections of physical with digital objects should work without difficulties, but this does not mean that digital and physical parts need



a) How to augment behind fence and/or branches?

b) How to illuminate digital object correctly?

c) Illuminate physical world with digital light



d) Shadow built by one light source and two objects; each of the three elements can be either digital or physical

Figure 4.3: Visual integration of digital and physical objects

to be visually adapted in such an extreme and perfect form so that the user is not able to differentiate between physical and digital objects anymore. The opposite is often the case. One advantage of having a mixed world is that for an augmented reality application an object can be of digital, physical or mixed form. An augmented reality developer can sometimes chose the form that is most favorable. For the user, it is often better to see the difference, so that he can benefit from the different characteristics of physicality and digitality and does not confuse them.

4.3 Examples for Connected Digital and Physical Objects

Connecting to an object's position: The connection most often used in augmented reality is certainly the linking of the position of a digital object to the position of a physical object. The digital object is usually at exactly the same place as the physical object is (see figure 4.4a). The connecting function simply assigns the position and often also the orientation of physical object to the corresponding.

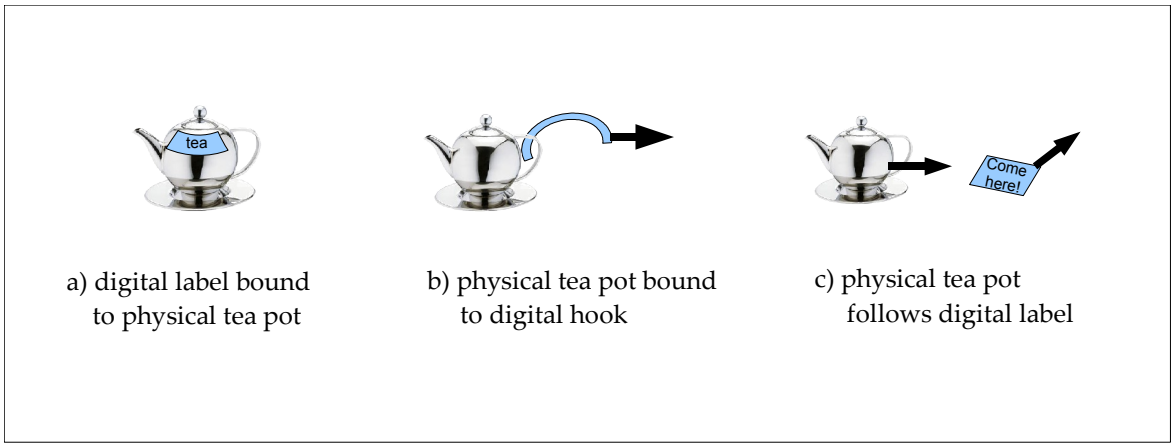


Figure 4.4: Connecting positions of digital and physical objects

We can also think of the inverse way that the position of the digital object determines the position of the physical object (see figure 4.4b). However, this is more challenging as it must be guaranteed that the physical object is really moved to the position of the digital object, for example by motors. A simple assignment of the physical position is not possible. The function needs to trigger events that make the physical object move. The position of the digital object is restricted by the inertia of the physical object, if the two positions should really be identical at all times. Another variant is to allow the free movement of the digital object and make the physical object move into the digital object's direction (see figure 4.4c). In that case, the connecting function takes the physical object's position and makes the physical object move to it. The dependency of the physical and the digital object's position is more indirect here.

Connecting to an object's temperature: In chapter 2, when we spoke about simulation of physical characteristics for digital objects, we already have mentioned that temperature of a digital object can be made feelable by a temperature sensing system or that it can be visualized using a color code that maps temperature on color. In the battery's temperature example (4.1), we visualized the temperature in the form of a bar, the height of which indicates the temperature. In this way, a physical characteristic temperature is linked with different characteristics of digital objects.

Other forms of catenation: In order to find as many types of linking as possible, we can do systematic approach. Every digital characteristic can be combined with a physical one.

Table 4.1 lists the different physical and digital characteristics in a matrix form. All in all, we get an enormous amount of variations, far too many to explain them all here. The table provides some examples. For specific applications, any form of linkings can make sense, so that no combination can be excluded. For instance, take a physical taste and a digital orientation: A bottle of milk in the refrigerator could be augmented with a digital thumb. If the milk is good the thumb points upwards, if it is sour it points downwards.

4.4 Establishing a Digital–Physical Connection

We now have an idea, how a mixed object can look like, but we do not yet know, how the connection of a digital with a physical object can be established. We will cover this in the following sections.

4.4.1 Problems with Establishing a Connection

Before we start a tracking system, the physical objects are not tracked. Hence, it is not known which objects there are and where they are. We usually have a reality model of an object that can be tracked. When a physical object is recognized we tell the reality model that this object is tracked. We provide the model with the information from the tracking or other sensor system, for example the position and orientation of the tracked object. But also other sensor data like temperature or object color can be measured and made available to the reality model. Some other characteristics of the physical object might not be tracked permanently, but instead they are measured once. This can be done for characteristics which are constant or which can be computed. Two examples — one about an objects form, one about its temperature — will explain this. They have already been explained in the corresponding sections in the sections 2.2 and 2.5 in more detail.

- **Unknown form:** The form of an object is often not tracked. Usually, the object is identified by a marker and the form of the object is known to the reality model in advance.
- **Computed temperature:** The other example is about a computed characteristic: we know the temperature of a physical object at a certain point of time, but we cannot measure it all the time. Additionally we have a thermometer that tells us the environmental temperature. We could then compute the temperature or even the temperature distribution of the object at all times from the initial value and the environmental temperature. However, this computation may lead to an incorrect reality model. For more information on that have a look at chapter 1 at the definition of the reality model.

There are to mention three more special issues of tracking:

- **Imprecise tracking:** The first one deals with imperfect tracking. Maybe an object can be tracked roughly, but it can not be identified exactly. Some objects might be similar, or tracking is so poor that it can not differentiate between them (see figure 4.5a). Here a small example: imagine we have two physical objects: a regular polygon and a circle. From the distance both might look equal. We could either say that tracking is not

Physical Characteristics	Position	Orientation	Size	Form Geometry	Material	Color Light	Temperature	Tactile Perception	Mass/Gravity	Kinematics	Phys Forces	Smell/Taste	Noise	Tracking (start/stop)	Access Rights
Digital Characteristics															
Position	Physical object's pos. defines digital object's position or inverse using motors	Digital slider physical rotary knob		Size of physical objects places digital icons at different location											
Orientation	Digital rotary knob moves physical object or physical slider position changes digital orientation	X									Visualize Magnetic fields with little arrows, orientation indicates direction of forces	See milk example from the text			
Size	Nearer physical objects have bigger (textual) augmentations, or inverse.		X								Size of digital objects indicates strength of forces				
Form/Geometry	Physical controller different positions different form. Edit points of digital form with position			X							Forces deform a digital object				
Material (mainly textures)					X										
Color/Light	Physical controller controls light					X	Color indicates temperature, very frequent application				illumin				
Temperature							X			Too high speed range in car: red blinking					
Tactile Perception								X							
Mass/Gravity									X						
Kinematics										X					
Phys Forces							When too hot, move away				X				
Smell/Taste												X			
Noise				Play sound for different geometrical forms									X		
Create, duplicate, delete														X	
Access Rights															X

Table 4.1: Matrix for connecting digital with physical characteristics

possible for such a fuzzy object, or we could see it as belonging to a group of similar objects for which at least some augmentations can be done that are valid for all objects of that group. In case a wrong augmentation has been done, however, a manual or automatic correction has to be performed.

- **Partially equally looking objects:** Now, let us assume that we have two cubes, with one different side, but five identically looking ones (see figure 4.5b). Though these two objects are definitely unequal, from a certain point of view they will look the same, what can also cause erroneous augmentations.

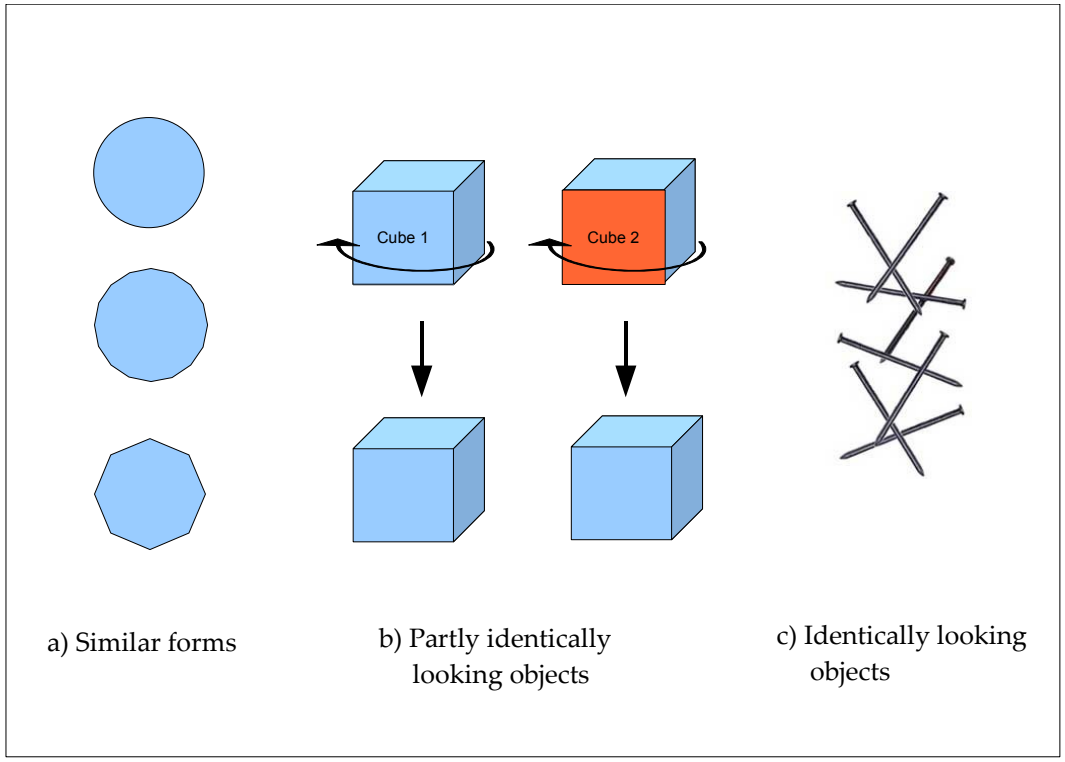


Figure 4.5: Similarities among physical objects

- **Equally looking objects:** The last issue of tracking to mention deals with objects that are very similar, so that they usually can not be differentiated without a special marking. Examples are equally–looking bricks, screws, or nails (see figure 4.5c). We discussed uniqueness and identification in section 3.3. In contrast to the aforementioned imperfectly tracked objects these identically–looking objects have the same characteristics. One of them could be replaced by any other.

4.4.2 Creating a Connection between Physical and Digital Objects

Having discussed these aspects on tracking, we will see their implications on digital augmentations. When a physical object is finally being tracked, we can look for augmentations that might be associated with the physical objects. In principle, there are two concepts about

how an augmentation can come into being. Either the digital objects exist in advance and are connected to the physical object or the digital objects are newly created for it.

Create a new augmentation: In the latter case, we have to create the digital objects first, as described in section 3.4. These can connected to their physical counterparts with any function (see section 4.1) between any of their characteristics (see table 4.1). For every tracked physical object, some kind of digital augmentations might be available. If the tracking system can not fully identify an object, but just manages to classify it, some general augmentations may be applied. Another way would be to let the user identify a newly tracked object and choose the digital augmentations and connections.

Connect to existing object: We can also establish a connection to already existing digital objects. This can happen automatically. If we newly track a uniquely identified physical object that has been connected to a certain digital object before, or that is specifically designed to be connected to a certain object, we might simply allow the connection. It can also happen that several mutually exclusive digital objects shall be connected to the digital object. Heuristics could choose the most adequate of those rivaling objects. For example, such a heuristic could be that the nearest fitting digital object is connected to the physical object. Another possibility is to let the user chose which objects the physical object is augmented with.

4.5 Dissolution of Mixed objects

4.5.1 Dissolution due to Interrupted Tracking

The counterpart to the initialization of tracking is a stop in tracking of a physical object. This can have several reasons. It could intentionally not be tracked anymore because it is not needed. Tracking might fail because an object is hidden by other objects or out of the tracking area of the tracking system. In case we have an augmenting digital object, we could think of destroying it also. This can be done if the digital object does not contain information that can not be reconstructed when the object is tracked again. If the digital objects that are connected to the physical object contain information on their own, they can not be deleted without losing potentially valuable data. The question is now, what to with those unconnected digital objects. Depending on the application there is a variety of possible alternatives. Here are a few (see figure 4.6):

- The depending digital objects could be made invisible (4.6b). This is usually done, when the digital object is very dependent on the physical object, hence it is a pure augmentation of the physical object and has no sense or no importance on its own.
- The connected digital objects simply become independent of the physical object (4.6c–d). It behaves according to the rules of the mixed world. For example, if it is possible for digital objects to hover in the air, it could remain at its last last connected position. If not, it might fall down to the ground.

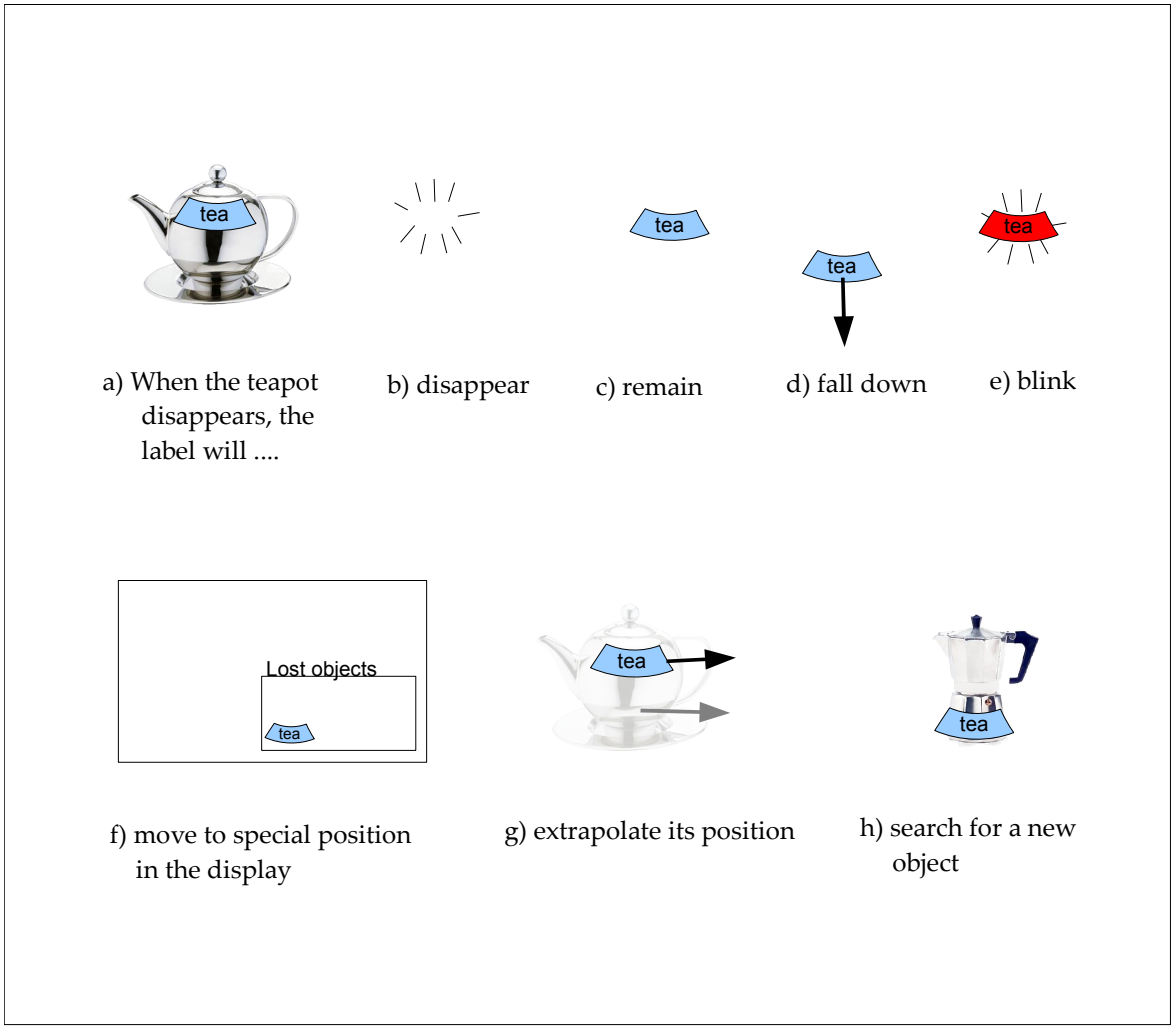


Figure 4.6: Dissolution of mixed objects due to interruption of tracking

- Digital objects could also perform a special action that is applied to disconnected digital objects(4.6e–f). For example, it could hover in the air though this would not be allowed for other digital objects. It could also be put to a special place where the user can see all disconnected digital objects. It could be highlighted or displayed in a different color to call the user attention.

- The digital objects behavior can also be extrapolated (4.6g). For example, if the object was moving before, this movement could be continued. This is especially useful, if the tracking of a corresponding physical object is interrupted for a short time and it is expected to reconnect as soon as it is tracked again.

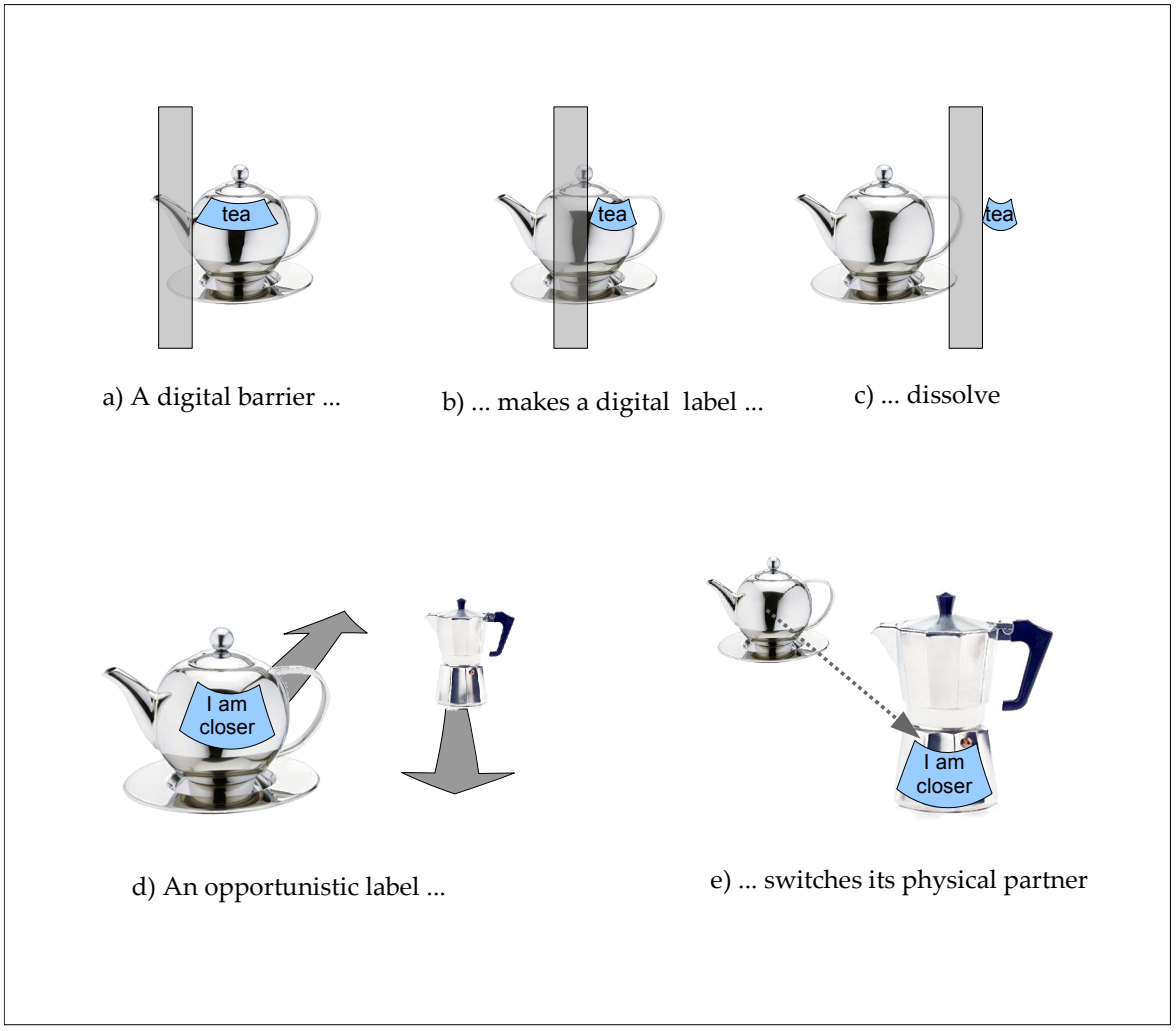
- As a last example, the digital object could connect itself to different physical object (4.6h). This is very useful if it should be possible to access and manipulate digital objects all the time.

4.5.2 Intentional Dissolution of Mixed Objects

When a physical object is manipulated, moved, or transformed, the depending digital objects need to react correspondingly. What correspondingly means, can not be said in general and can be anything the connecting function (see 4.1) requires it to do.

Sometimes, the physical objects change in a way that makes the connection dissolve. Such a separation can be triggered by the recently addressed interruption in tracking. It can also happen voluntarily.

The dissolution can also be provoked by digital barriers (see figure 4.7a–c). For example, assume that there is a digital wall that a digital object bound to a physical one can not permeate. When we now move the physical object out of the digital barrier, the connection to the digital object might get lost. In this case, a digital object causes the separation of a physical with a digital object.



a) A digital barrier ... b) ... makes a digital label ... c) ... dissolve

d) An opportunistic label ... e) ... switches its physical partner

Figure 4.7: Intentional Dissolution of mixed objects

Also another physical object could cause such a dissolution (see figure 4.7d–e). Imagine a digital object that can be bound to one of two physical objects, but not to both. We assume that the digital object behaves opportunistic. It always prefers the physical object as partner that is best for itself. When the other object is more favorable, it switches its connection. It should be mentioned that this switching of two connections could also be considered as one connection between one digital and two physical objects. It is a question of augmented reality design which concept is implemented for a given situation.

4.6 Replicating Mixed objects

In the section 3.6 we have spoken about how to duplicate digital objects. Replication can be either used for creating independent copies or for creating additional physical representations of a single object. Furthermore, we have seen how cloning can be used with digital parts of mixed objects. For environments with digital, mixed, and physical objects, new ways of using copies can be thought of. Next to copies of digital objects we could think of other forms like replicating a physical object in the form of a digital object.

Duplication makes sense especially in collaborative environments (what will be addressed in chapter 5), because conjointly working people can have their own replicate of important objects. For mixed objects, a great variety of replication can be thought of. A physical part of a mixed object can be realized as a digital or physical part in the replication. The same applies to the digital parts.

4.6.1 Replicating Digital Parts of Mixed objects

An operation that makes working with digital objects effective is the possibility to duplicate them easily. This avoids doing the same work twice. With mixed objects, duplication is somewhat more difficult to achieve. In fact, fast duplication can usually be performed for the digital parts only. For mixed objects a duplication of these digital parts could make sense in different situations. Let me give three different examples (see figure 4.8)

- A digital duplicate of a connected digital object could be connected to the same object (4.8b). Imagine a physical object with a digital label on it. In a multi–user environment a second spectator could not read the digital label from his point of view. A duplicate of the digital label could be created for him to better read the labels content.
- As an alternative to that, the digital duplicate might not be bound to the physical object its original is bound to. Instead it becomes a free digital object (4.8c).
- A third useful way of dealing with the duplicate is to bind the it to another physical object (4.8d). In particular, if there are identically or similarly looking physical objects we can attach them with the same digital objects. In this way, augmentations can be copied to other objects.

As already stated in section 3.1.3, a duplicate can either be an additional visual representation of one digital object, or it can be an independent copy if it should be modified separately without interdepending after the replication process.

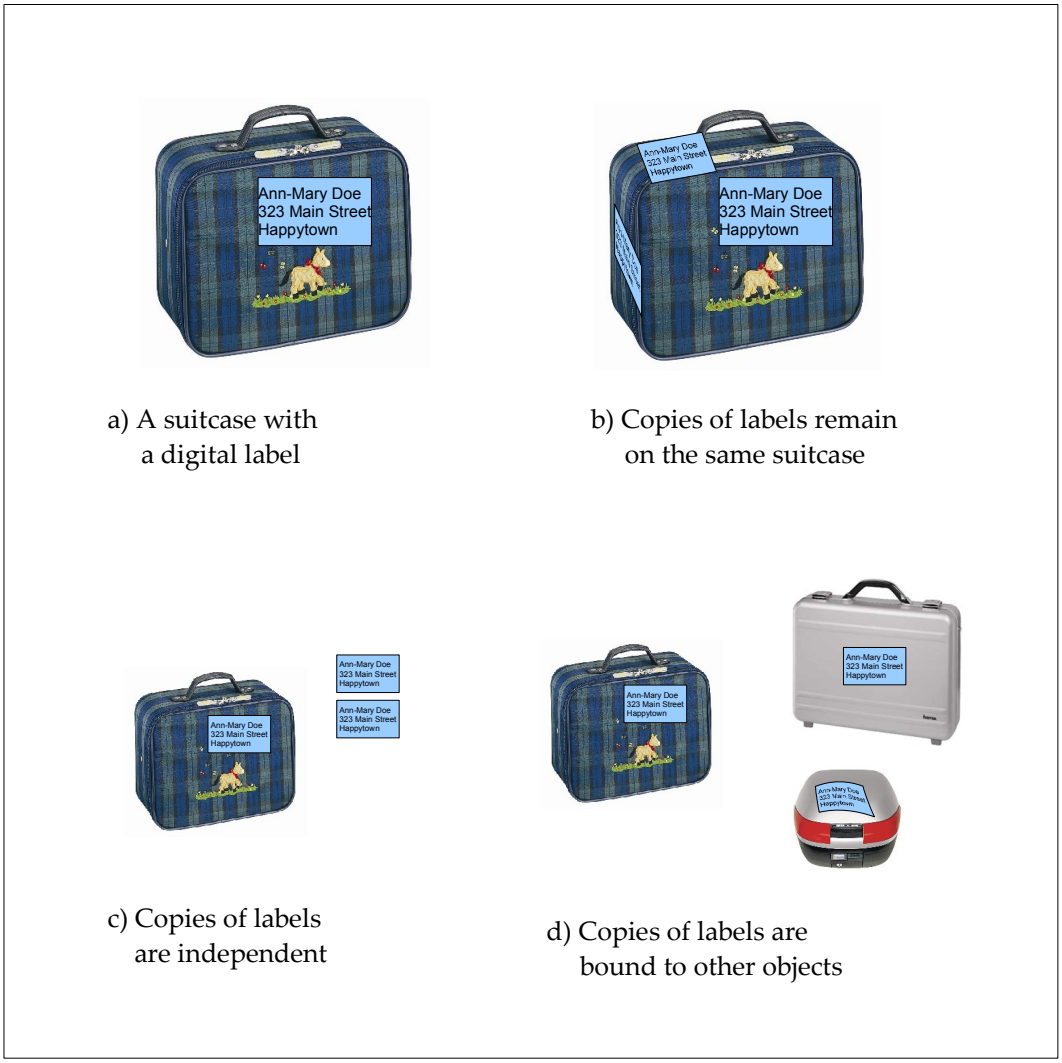


Figure 4.8: Replication of digital parts of mixed objects

Changes of digital components often have no influence on the physical objects. This can be traced back to the lack of physical actuators in most of todays augmented reality applications. Section 4.2 provided us with some ideas on how new physical objects with sensors and actuators could change the passiveness of physical objects.

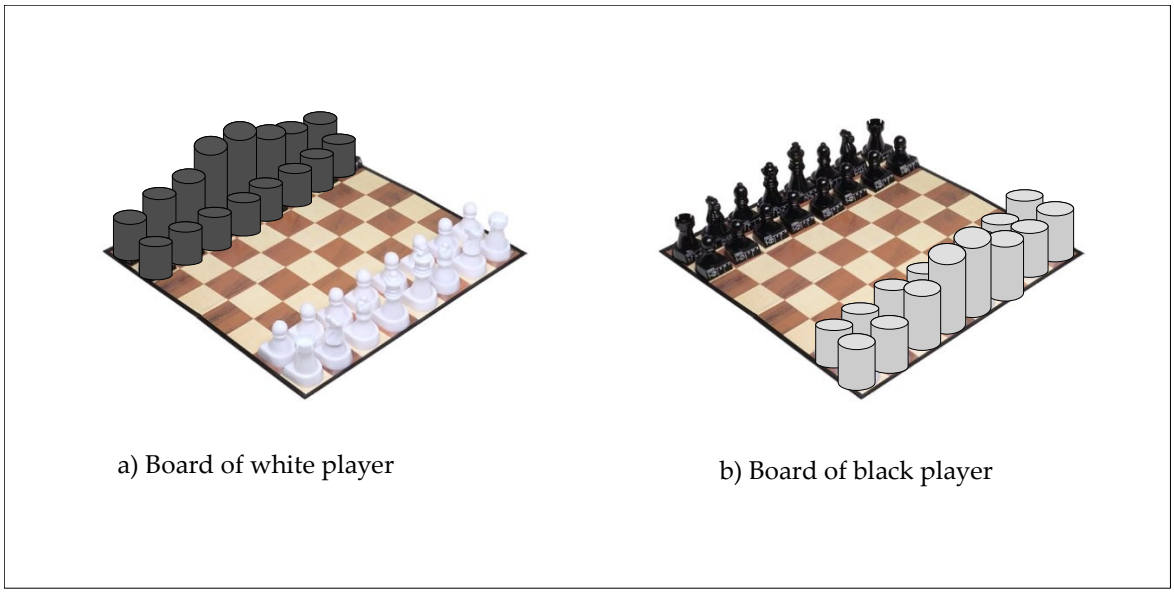
The same applies to the deletion of a digital object. Often, the removal of digital objects has no consequences for the physical object.

4.6.2 Digital Copies of Physical Objects

Before we think about replicating mixed objects, we will first discuss purely physical objects and their purely digital duplicates. Let us take a physical cube as an example. This cube should be the only physical element so that all its copies are digital objects. The digital cubes

could imitate some actions that are performed with the physical cube.

As a second example an augmented chess game is given (see figure 4.9). There shall be two boards — one for each player. Each contains half a set of the physical tokens. Each player sits in front of the board that contains just his own tokens. While playing, the tokens are tracked and a copy of them are augmented to the board of the opponent. The user can only move the physical tokens; the digital tokens are locked for him. In this way, it is assured that only the owner moves the stones and not the opponent. In this example the differentiation of physical and digital replications supports the rules of the game.



a) Board of white player

b) Board of black player

Figure 4.9: Augmented chess with digital copies of tokens

A different variant of that chess game could allow the interaction of the physical with the digital stones. Imagine the following idea: One player throws a digital token out of the board with physical token. For the opponent the situation is inverse. A digital token throws one of his physical tokens out of the board. If no actuators are available that move the physical token he needs to be instructed to remove it himself.

4.6.3 Copying Mixed Objects

For mixed objects we have even more possibilities how replication can be done. It is probably best to split up the mixed objects into is components. These are either digital or physical. In the copy these components can also be the one or the other. We get four possibilities for the replication of a single component. Table 4.2

Digital copies: First, think of having a merely digital copy of a mixed object. Both the physical and the digital parts of the mixed object have a digital equivalent at the copy. It can be an advantage to have a purely digital object, for example, if the mix of digital and physical

Original / Copy	Physical part	Digital part
Physical part	Find or create two equal or very similar physical objects.	Create or find physical objects with characteristics of digital part. Establish connection to related digital parts. Actuator could help.
Digital part	Digitization of physical object, use information from reality model of physical part. Connect to related physical parts	Replication as for copying digital objects

Table 4.2: Copies of objects with varying physicality and digitality

parts does not integrate well and a monolithic representation provides a better impression. For other scenarios in contrast, such a uniform digital representation can cause confusion, as somebody who works on the digital object can not know, which parts are physical at the mixed copy. The digital parts that have a physical counterpart might show an unexpected behavior and cause confusion.

Mixed copies: Copies of mixed objects can be other mixed objects, where different parts are physical. This can be useful if two or more persons work together and each one should only modify some parts. These parts should be the physical parts, or the parts influenced directly by the physical parts. We have already constructed an example for this. We just have to consider the board and the tokens of chess example as one mixed object.

We can run into difficulties when physical parts of the duplicates are not in a congruent part. Figure 4.10 shows such an example. Each augmented mobile phone has two physical parts. The orientation of the physical parts does not allow the augmentations to be geometrically similar. In order to achieve similarity, the physical components would need actuators so that they can move into an appropriate position an orientation.

Another possibility of achieving consistency among physical parts of mixed objects is the following: we could allow the overprint of physical objects by digitally modifying them in the user's view.

An example: Imagine a review where some persons review a text (See figure 4.11). Everyone has a physical copy of the text. If someone annotates or overwrites something in his text, these modifications could be projected as digital corrections at the other copies. It could also be possible for the persons to do this modifications digitally. For the others, it does not matter whether the annotation or overwriting was done physically or digitally. The digital correction could be made visible in their view in every case. In general, this turns previously

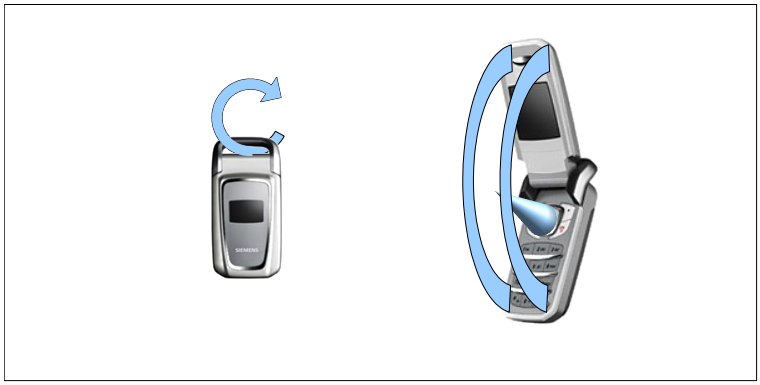
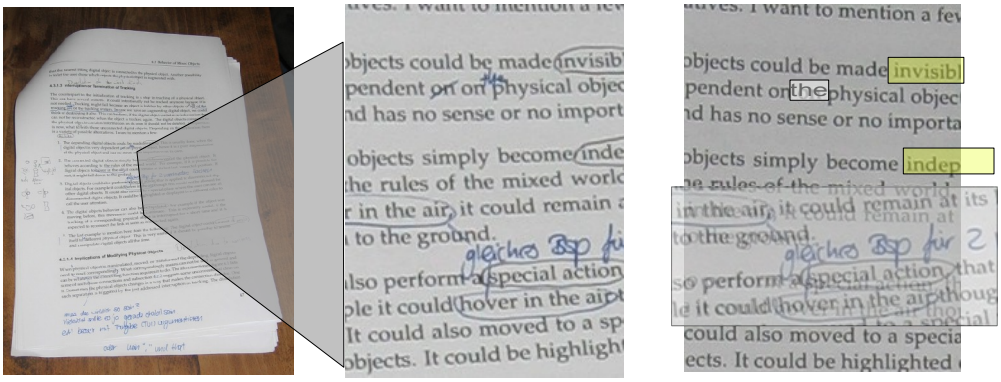


Figure 4.10: A copy of a mobile phone with non–replicable augmentations

physical objects into mixed objects. The users will start with physical copies of a text. By physically or digitally modifying them, the copies become augmented objects. This example can be applied also to other duplicated objects in a mixed world.



a) A text with annotations

b) Copy of the text with augmented annotations, partly PC-created, partly an overlay from a)

Figure 4.11: Overwriting physical objects digitally

There are to mention two limitations regarding this technique. Firstly, if see–through displays are used for the augmentations, an overwriting of the text will not work well, because the display is semitransparent. The original text will always be seen. Secondly, just overprinting a physical object does not modify them physically. If we, for example, delete a physical obstacle by digitally removing it, it will remain their an show its present if somebody stumbles across it.

4.7 Resume Work within Augmented Worlds

In the chapter on digital objects, we discussed how digital objects can be saved and the work on them be restored and continued. We will now look for possibilities and challenges of terminating and continuing the work within mixed applications.

We will give some options on what can be done, so that the user can continue his work. It should be mentioned that these are only suggestions out of a large solution space. There could be other completely different ideas on how to restore a scene that may be more appropriate in a certain situation.

In the following sections it is assumed that all digital parts, as well as the information that the reality model provides can be saved and recovered as described in section 3.7. Imagine the situation in figure 4.12a. All digital components have been saved. Later, the interaction with the augmented scene should be continued. However, some physical objects have been moved or even removed. When the augmented reality is started again, we can chose between varying degrees of restoring the previous scene.

4.7.1 Restart Work with Given Physical Set–up

In the first scenario, the user simply starts the program. Whereas the completely digital objects can be restored, the question is, what to do with the partially or completely physical objects. A first idea is, augment the identified objects objects with the same physical objects as on program termination. Removed objects are therefore not displayed. As soon as a known object is again put to the desk, the attached augmentations are displayed.

Problems can occur if it is not possible to track such a object uniquely. The difficulty in this case is that, for example, physically equal objects with different digital content could not be reassigned to that object it was connected to before. As long as we assume that every object has a unique ID and that a tracking system can identify such an ID, there is no problem.

But also in the ambiguous case there are ways to cope with that. For example, there could be a pop–up window that asks which augmentations this objects should be attached to and maybe the possibility that this object is a completely new one.

The bad thing about this scenario is the fact that some information on the previous work is lost. Maybe the main work of the day before was the arrangement of the objects. For all partly and completely physical objects the information about their position is lost. The positive thing is that it is not necessary to reconstruct the previous situation, what may cause some work. The previous position of each physical object would have to be found and the digital components needed to be re–attached. Instead you can simply start working.

4.7.2 Reconstructing the Previous Situation

In the second scenario we want to avoid the loss of information of scenario two. All digital information that was stored the other day is loaded and displayed. The purely digital objects are displayed according to the first scenario. Physical components that have not been removed can be attached with their augmentations as it was the other day. For the partially

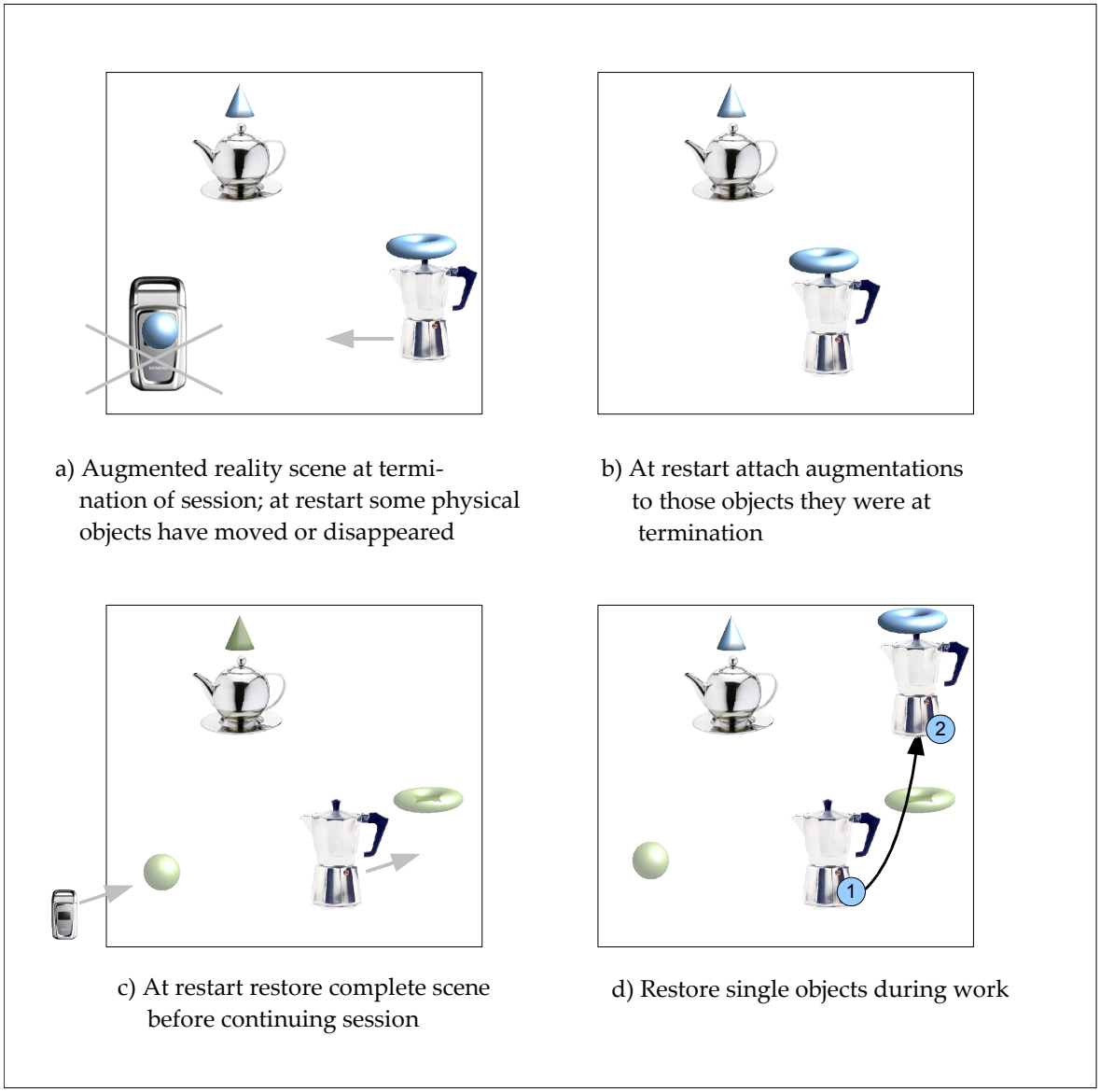


Figure 4.12: Restoring an augmented scene

or wholly physical objects that have been removed a placeholder for the physical parts together with the augmentations could be displayed. It should also be displayed which objects are complete (in the sense that they have all physical and digital components). Objects for which physical or digital parts are missing should also be displayed so that they can be distinguished from the other ones. Let me give three ideas how the incomplete objects can be ”reunified”.

4.7.2.1 Complete Rebuild of Mixed Objects

One possibility is to put all objects back at the place they were before (see figure 4.12c). Therefore, all digital parts are restored with a lock, so that they cannot be moved. Digital placeholders indicate former position of the physical objects and when a it comes close to digital counterpart, the latter one is highlighted. This is done for every physical object. When the scene is completely rebuilt, the digital parts are unlocked and the work can go on.

A question is, whether the objects can be identified uniquely. If not, it might be annoying, for example, when there are a lot of digitally diverse but physically equal objects, maybe 20 or 30. The same applies when the unique ID cannot be seen. One has to try every empty object in order to find a fit for the single digital counterparts until the correct one is found.

If the objects are not unique, they could be confused. Maybe some objects contain physical information written on it that is not known to the augmented reality system. An advanced handwriting recognition could prevent this. But also a simpler pattern matching algorithm that can recognize the notepaper but that does not necessarily recognize the objects content would suffice.

A negative aspect here is that the work can not be continued until all objects are at their place. In case some objects were lost, we run into problems. Another issue is that the physical components can probably not be put at the place they were before. Just imagine the table at which the objects were would have been removed.

4.7.2.2 Partial Reconstruction during Work

A different method is, not to wait until all physical objects are at their place but to unlock and attach the locked digital objects when a related physical comes near to it. The user simply has to catch the digital objects with the physical ones and continue your work. This could happen also the other way around. maybe a heavy tracked table has been moved but cannot be moved back. Then the digital counterpart could be moved to the physical one.

4.7.2.3 Automatic Reconstruction

A very useful application could be the following: imagine that there was a little tremor, so that most physical objects have been moved a bit but in slightly different directions. The general structure, however, was not destroyed. A pattern matching algorithm could recognize that and reattach all digital components to the physical ones. Similar to the last idea of the previous scenario, the digital parts have been moved in order to do the reconstruction.

5 Collaborative Work with Physical, Digital, and Mixed Objects

There are many tasks in our world that one person can not perform on his own, but jointly he can make it. Human beings have always cooperated successfully in history. However, even today most computer software does not support collaboration. This is due to the fact that most software runs on PCs. The Personal Computer — as its name already implies — was originally designed for personal use, thus one person working with it. Collaboration was not foreseen.

Nevertheless, nowadays there is a lot of software specifically designed for collaboration, for example video conferencing software, collaborative text editors, but also computer games have multi–user modes. There exist, for example, racing games, where the player act in a competitive way, whereas the some commonly–known action shooters offer the possibility to form groups and fulfill certain missions conjointly.

Also for augmented reality applications, collaborative support could bring considerable improvements. As collaborative augmented reality differs from collaborative PC software, there are many research groups that develop collaborative augmented reality applications. Especially on collaborative augmented desktops seems to produce interest.

Focus: In all forms of team–work the essence of collaboration is in a conjoint work with common objects, be they physical, digital, or mixed. Of all aspects of physical and digital objects, we discussed in the last three chapters, here we will focus on visualization. This means that we analyze collaborative solutions regarding a reasonable graphical integration of the involved people. The illustrated ideas could be transferred to most other aspects, for example, to acoustics. Instead of a conjointly used display table we could have a speaker, which can be heard by anybody. The same way, headphones can replace individual displays and headset microphones can replace private mouse pointers or text cursors.

In the following, we will describe a few kinds of typical collaborative set–ups and give examples for imaginary applications. As just indicated, the most important criteria will be the visualization. The way of collaborating differs depending on whether the users have the same view of the world or a different one. We will not emphasize at the same place or remotely with each other and whether they.

Existing collaborative software and virtual reality software will be analyzed. The discovered concepts will be discussed regarding to their applicability to augmented reality applications. The insight gained from the previous chapters will be useful in providing solutions for such a transfer.

5.1 Work with a Collaborative Display

First, we want to discuss how collaboration can work, when the users have the same view of all objects, realized by one display. This can be a common display or a video projector, which displays digital objects either on a wall or on a special table (see figure 5.1a).

User Interface for Collaborative Desktops In order to collaborate efficiently, each user must be able to interact with the system. It is not a good idea to provide only one user with a special input device, if equitable collaboration is desired. For example, if only one user has keyboard, the other users are excluded from entering text. The introduction of a multiple input devices does not solve the problem either. If only one mouse pointer is available that can be moved by every user, the people will compete in using it. Because of that, it is hard to reuse standard software for team–work by projecting it on the table. Instead collaborative user interfaces has to be designed that allow concurrent multi–user interaction.

Collaborative Desktops in Augmented Reality: Software that is specifically designed for the use with collaborative tables, can easier be used for augmented desktops. For example, Wolfgang Stuerzlinger designed an interesting multiuser display in [60]. For mixed reality applications such desktops are often favored to solutions with head mounted displays, as they have two advantages. Firstly, for most users it is inconvenient and exhausting to ward a head mounted display for a longer time. Secondly a desktop display is at a fixed position so that the digital–physical overlay can be performed more exactly and without jittering.

For using physical objects with the software a tracking system is needed. Next to augmenting the tracked physical objects, we can also use them in another way: It seems to be interesting to replace the traditional input devices and the corresponding widgets by physical objects. Hiroshi Ishii [56] calls them “phidgets” for physical widgets. An example for such phigets is a magnifier consisting out of a metal ring without lens and a handle [28]. The lense is simulated by the software. Every digital object that we see through the ring will be magnified. Such phidgets allow a very intuitive handling. Many other widgets that we know from desktop software and that are used for scaling, aligning, color manipulation can be realized as phidgets.

5.2 Collaboration with Individual Displays

Having only one display available for a group of users leads to some restrictions. The displayed perspective is the same for all users. This is unfavorable, if three–dimensional graphics should be displayed on a table display. Furthermore, the users can not make individual decisions, for example, on the font size of the displayed texts. We do not face such restrictions, if everybody has its own display. The users can choose a point of view on their own and visualize different aspects of the digital world (see figure 5.1b–d). In this section, we want to consider solutions in which the conjointly used digital objects look the same for everybody. Only the point of view can be chosen independently. In the next section we will also discuss ideas with more individual views.

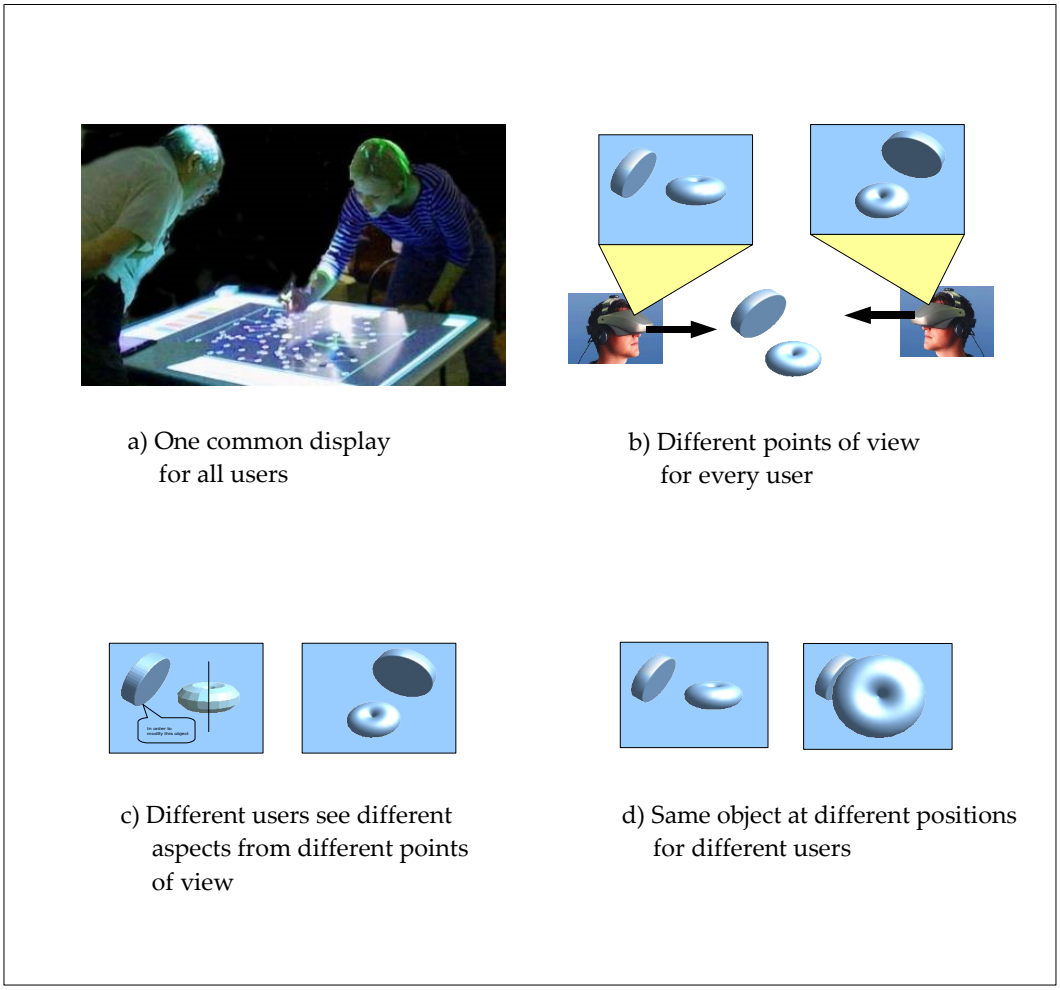


Figure 5.1: Different kinds of collaborative set–ups

Collaborative PC software: In order to get ideas that are possible with such multiple displays, collaborative PC software may provide some suggestions. Let us take a collaborative text editor as in figure 5.2. People can concurrently work on one text, and each user has his own cursor and everyone can freely scroll around. The document is the same for all participants and modifications can be seen immediately by anyone. The different point of view in this example is given by the different segment of text that the users see.

Collaborative virtual reality: This is similar to the conjoint work in three–dimensional digital. Let us assume that there is a common place of interaction and every user has a head–mounted display. Although the single displays show the world from a different point of view, the digital world should locate one digital object at the same physical position. This way of displaying information is very close to our usual perception of nature. Therefore, human beings have an intuitive feeling how they can collaborate.

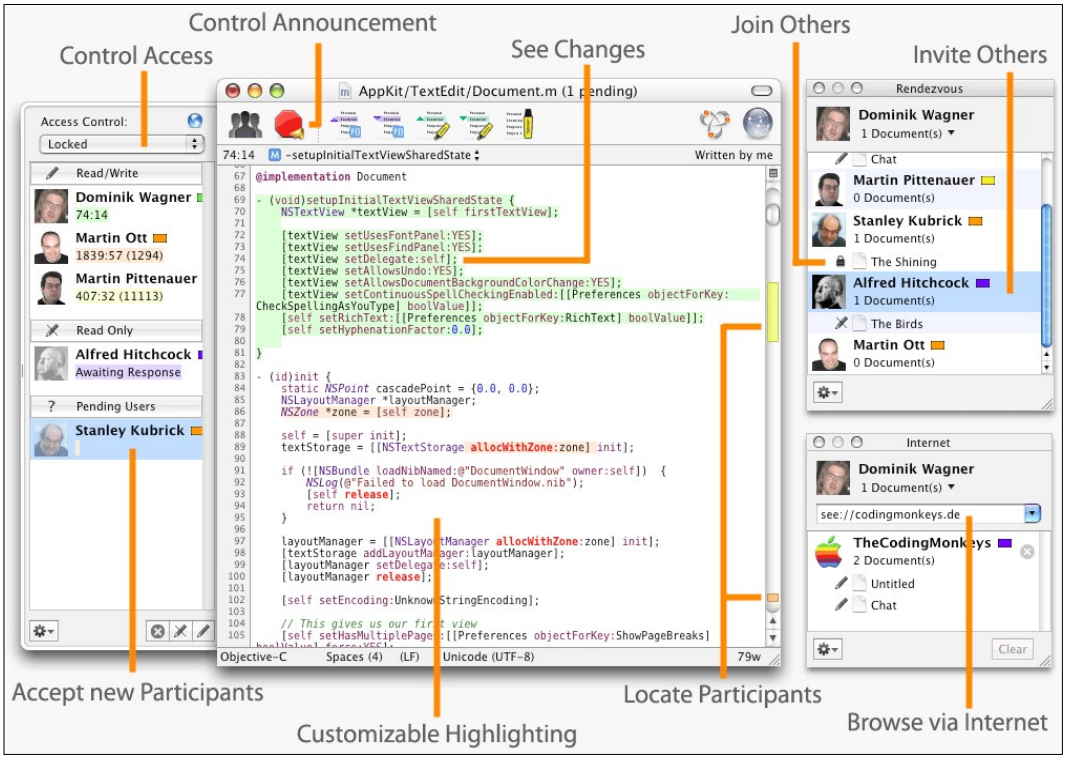


Figure 5.2: A collaborative editor

Collaborative augmented reality: This form of collaboration can be transferred to augmented reality applications. There are two big advantages, when all users see the same world with the only difference being diverse points of view. Firstly, introducing physical and augmented objects can happen without major concerns about a diverging of the single visualizations. That way it is possible to integrate these objects seamlessly with digital parts. Secondly, the users can imagine what the colleagues see. Misunderstandings due to different or omitted objects can be avoided.

The only objects, we will allow to be individual ones, are display fixed digital object, like menus or icons. For such objects, it is intuitively clear for the user that they are personal elements that can not be seen by the others.

5.3 Collaborative Work with Diverse Visualizations

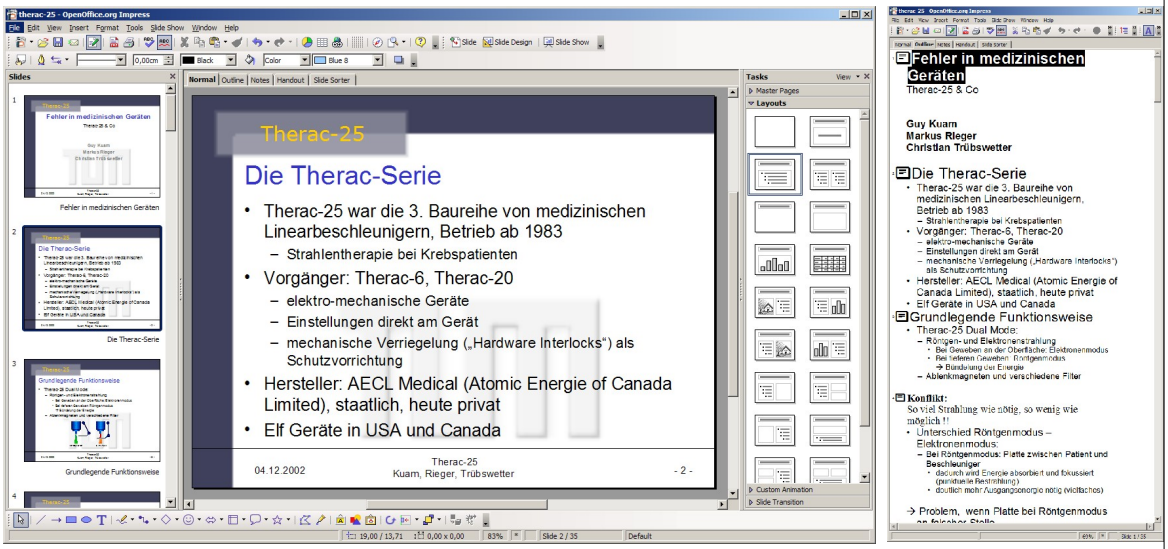
Now we want to discuss collaborative scenarios, which allows different visualization of the world for the single users. A more independent and also individual view can be achieved thereby.

5.3.1 Viewing Different Aspects of a Scene

For certain tasks it is an advantage that different users see different aspects of the same object as in figure 5.1c. In using and combining the different information on the digital objects the users may gain a deeper understanding that a single user could not achieve.

PC software: Again we will look for desktop software to see the benefits of different forms of views. This time the software is not even collaborative. Let us take a common presentation slide designer (see figure 5.3). Usually, there are various viewing modes: one for editing, a print preview, a structured view and so on. A person could choose the document view according to his individual preferences. Maybe older persons may choose a view that displays the letters with a larger font, so that they can read better. Others are interested in a realistic "what you see is what you get" representation (WYSIWYG) or in a more structured view. The users can switch between the different views in order to perform different tasks.

When different views are used in collaborative software, this brings also negative side effects. For example, not all digital objects are visualized in every view. The structured view might not display graphics. This could also cause confusion, when some users speak about or modify objects that others can not see and are therefore not sure about their existence or location.



a) Layout view of a typical presentation program

b) Outline view

Figure 5.3: Different viewing modes of a typical presentation designer

Graphic design in virtual reality: Different views could also be applied to virtual reality applications. Let us assume that two users are creating a three–dimensional scene, maybe for a computer game (see figure 5.4 and [42]). One of the scene designers could see a fully colored and textured scene. He sees the scene as the future gamer will see it and can therefore decide, what looks good and what not. The second designer, instead, sees the scene in wireframe mode. He can better see hidden objects and the structural setup of the scene. In this way, it can be assured that the scene has both a nice look and an intelligent scene design without switching the view all the time.

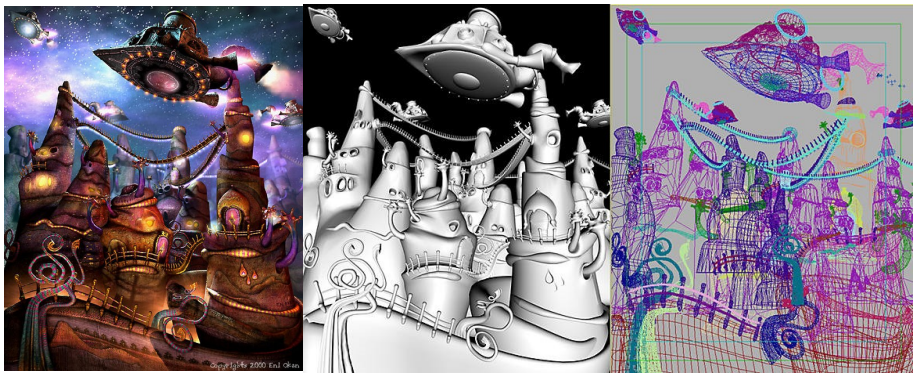


Figure 5.4: Collaborative work with different views of the same scene

Transfer to augmented reality: The enrichment of such software with physical and mixed objects does not complicate the team–work. Instead, collaborating people can benefit from them. Usually (if the visualization system if not too realistic), the people can differ between physical and digital objects. For the users it is clear that the physical objects must be the same for everyone. Because of that, the physical objects can act as a point of reference when the single visualizations differ considerably from each other. Besides, different kinds of augmentations of a physical objects will enable similar benefits as described in the scene designer example.

5.3.2 Allow Different Location and Orientation of Identical Objects

In the case of individual displays, there are lots of possibilities in varying the views for the interacting persons. For example, the same digital object can have different color for different users. Maybe some objects do not even exist in certain views. Of all these variables, we want to discuss two of them in more detail: position and orientation. The same digital object can be placed at different locations and orientations for each person. This will lead to misunderstandings, however. The diverse forms of replicating physical, digital and mixed objects, mentioned in 4.6 has delivered proposals on how to resolve this issue.

There are various situations in which it makes sense to visualize a digital object at a different location for the single users. A digital text label might be moved close to the user and its orientation changed, so that the user is able to read it. The differing object position leads to different perceptions of the digital world. The users do not know where other users see the objects. Pointing at the object does not work in the augmented world if the object is displayed at different locations. Not even advices like "Take the digital object that is nearest to you" can solve the problem

By applying replication techniques, we could do so (see figure 5.5). When a user points with his finger (or a different pointing device) on such an object, the second user can not see this finger pointing at his object. We solve this by reproducing the finger digitally, so that it points to the corresponding point in the second users copy.

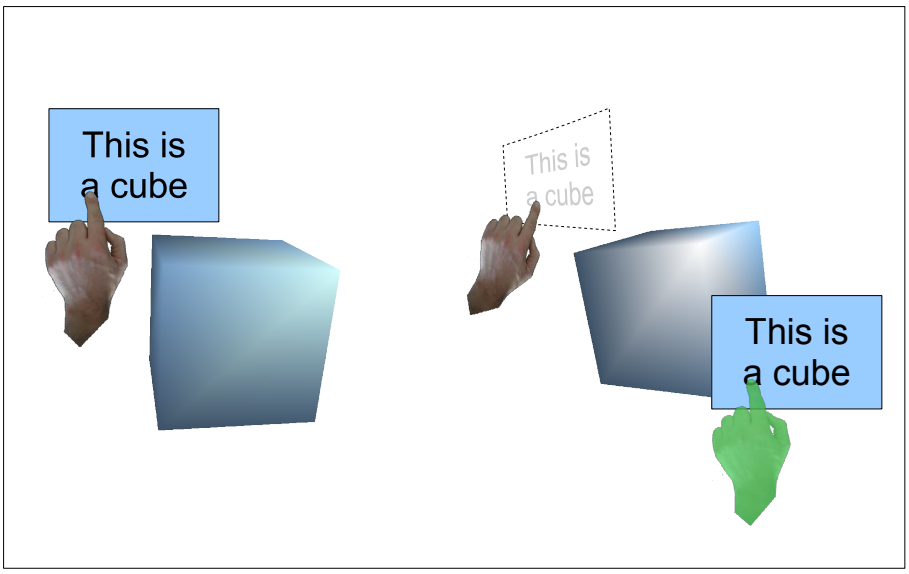


Figure 5.5: Individual positioning of text labels

To sum up, different visualization modes make collaborative interaction more complex and therefore require higher skills. The big advantage is that concurrent interaction under different aspects is made possible. Complex tasks can be performed that one user is not able to do on his own. Solutions for virtual reality can be used for augmented reality systems. In this way, collaborative work on physical, digital, and mixed objects can be improved.

6 A CRC Cards Application with Physical, Digital, and Mixed Objects

After having discussed so many different aspects of physical, digital, and mixed objects, we want to see how a method that supports object–orientated design is performed under different degrees and constellations of physicality and digitality. First, we will see how this method was originally using physical cards made of carton and containing textual information. After that we will see, how this method can be transformed into a computer application. In a next step, we will see how such an application can be designed using augmented reality techniques. We will also consider scenarios where some cards are made of carton, some are digital, and some are augmented. Eventually, we will draw a conclusion on the different scenarios.

In order to find out the advantages of the single scenarios in practice, a piece of software was written that demonstrates the working with physical, digital and augmented cards. In testing and using this software the relevance of differences can be estimated in a better way. It should be mentioned that the software was not designed for the production use. It was rather written for testing and illustrating differences of digital, physical and mixed objects within a useful scenario, thus giving a consistent example for the theoretic model proposed in this work.

6.1 Design of CRC Cards

In object–oriented programming, so–called CRC cards are used in order to find classes and their relationships. They were invented by Kent Beck and Ward Cunningham who also formulated the “extreme programing” paradigm together with Ron Jeffries [5]. CRC stands for Class–Responsibilities–Collaborators. Sometimes the word “Class” is replaced by “Concept”, the two latter words are either found in singular or plural and sometimes “Collaboration” is used instead of “Collaborator”. We chose the first version mentioned because one card describes one class and contains several responsibilities and collaborators. For each class, we have a card that approximately looks like that one shown in figure 6.1. On the top of the card there is the name of the class and its superclass and subclasses. Below that part, the card is separated in two columns, one representing the responsibilities of the concept, one representing the collaborators. The responsibilities are attributes or methods that the class contains and controlls, collaborators refer to further classes that this class deals with.

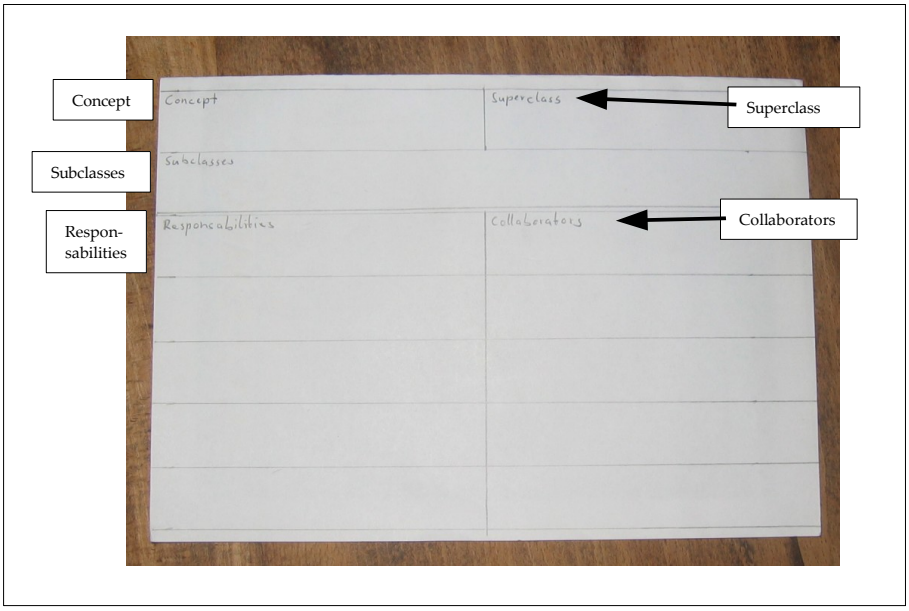


Figure 6.1: A typical CRC card

6.2 How to Use CRC Cards

Originally designed for teaching programmers the paradigm of object orientation, CRC cards are increasingly used at different hierarchies of software design; they can be used for software architecture or for detailed object design. They have also been used for conceptual planning of business logic software. A main reason for choosing CRC cards is that they support teamwork. Several people can sit around a table, everybody can participate in the design process by making suggestions, picking and reading cards, writing on cards. The cards can be aligned as wanted. When there are several cards on the table, they can be grouped, so that the cards that have strong interconnections are close to each other. The interconnections are given by the collaborators on the cards. At the beginning of a project the users usually start with empty cards. While designing, more and more new cards are introduced. The users should also be encouraged to cancel or overwrite existing card entries. If a part of a solution has been found to be unfavorably, it can be removed and redesigned. Also groups of cards that seem to be completed can be removed or put together to a pack of cards in order not to lose the overview.

6.3 Digitalization of CRC Cards

CRC cards were intentionally invented as physical entities in order to promote collaboration and the paradigm of object–orientation. Another advantage is that a table provides a relatively large space for the cards and the information they contain. A single small display can not support collaboration or provide the necessary space to that degree. Despite this facts it has been tried to implement software versions of CRC cards. One example is the UML

CASE tool[1] "Visual Paradigm for UML"[61] that offers CRC cards as UML–diagram type (see figure 6.2).

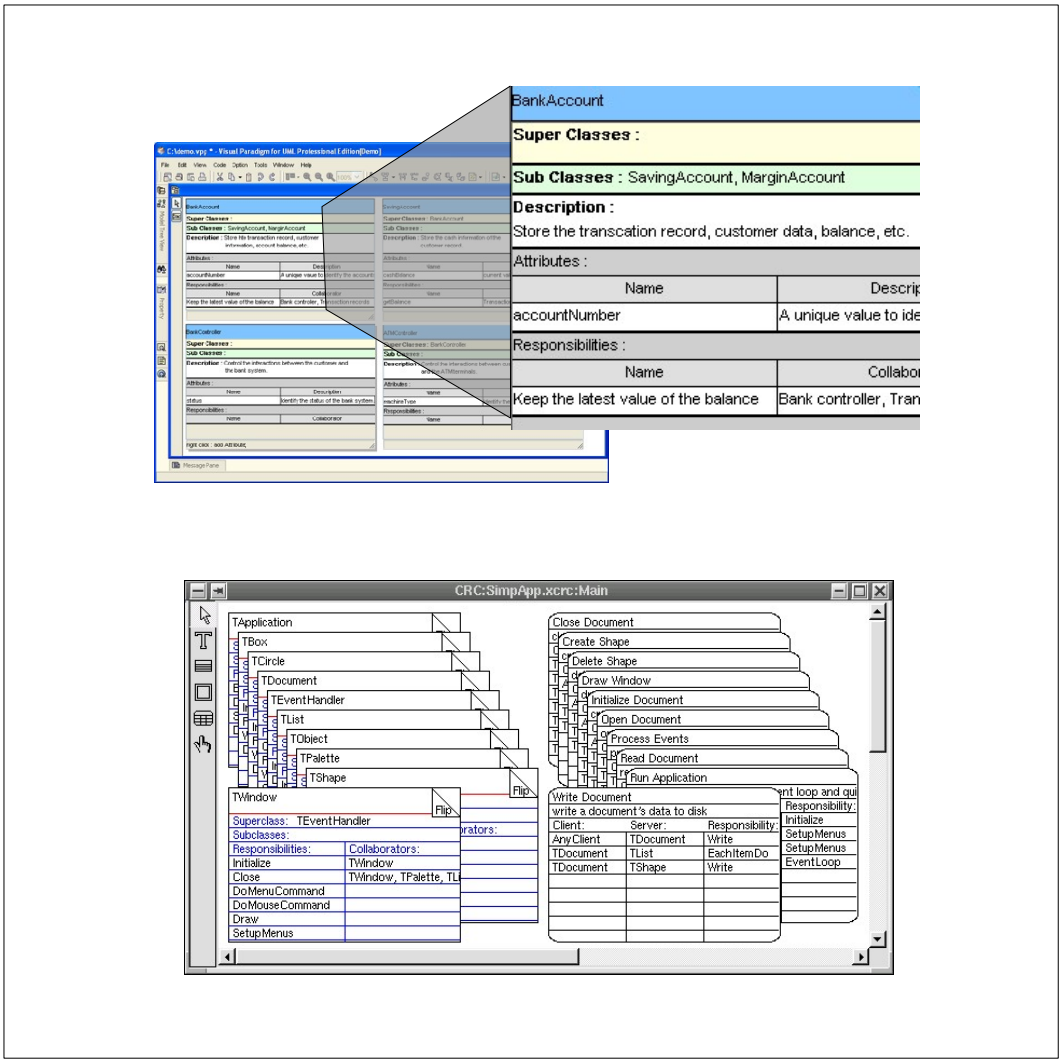


Figure 6.2: CRC cards software

Also the CRC cards software developed for this thesis enables us to create, edit and move digital CRC cards. The control of the cards is exclusively realized with the keyboard. In case a card is found that has the same class name as the collaborator of another card, a connection is drawn between the two cards. In that way, it can always be seen which cards collaborate, even without reading all the collaborator entries on each card. This is especially useful if a redesign is performed. By removing or changing certain entries, the implications on the corresponding collaborators become immediately clear and will not be overlooked.

[1]UML means "Unified Modeling Language"; CASE means "Computer Aided Software Engineering"

6.4 Designing a Mixed CRC Cards Application

When we want to create an augmented CRC application, we can decide relatively freely which components of the object should be realized digitally and which physically. This is in stark contrast to other augmented reality applications, which impose stronger restrictions. For example, if augmented reality is used for diagnosis of a defect machine, it is obvious that the machine itself is physical and the diagnosing information are digital. In other areas, however, like teaching or gaming, an application designer can choose which objects are realized as physical entities and which ones as digital entities. In our case, we deal with creating information. We want to identify the most important elements of our application. We have a table, card bases (in the sense of the medium that carries the information on the card), structuring elements that are printed on the card, text entries on the cards, and connecting lines (see figure 6.3). With structuring elements we intend to denominate the lines delimiting the text fields and the text describing the card structure, for example the words "subclass" or "collaborators". It might be tempting to ignore some solutions from the beginning. For example, most people would not think about making the table digital and the cards physical. However, we will think about how such alternatives could look like. By doing a systematic approach, we can discover a solution that we would not have thought about.

6.4.1 Elements for the Application

A table for the CRC cards: So let us think about a digital table. We might think that, in order to put a card on it, also the card should have a digital form. A physical card would not remain on a digital table and fall down to the floor. (We assume that we always have a physical floor, what is mostly true, as long as we do not stand in front of an abyss). In case we have digital cards, we have no problem. When we instead make the cards physical, we need something that makes them lie on the digital table. For example, we could make the floor and the cards magnetic. A magnet in the floor could be controlled electronically to simulate the physical forces that a physical table would impose on a card.

However, we have to take into consideration the goals of our CRC card applications. A physically correct reproduction of the original CRC card scenario is not necessary. It can be valuable at least to think about such — at first sight unusual — ideas. Thereby, we might find alternative or even better solutions. In our case, we choose the table to be a physical one. The implementation of a scenario with a digital table would require too much work on the actuators needed and their control. Furthermore, we lose the possibility for the users to sit around a (physical) table, to touch it, and, even more important for the application, we can not use physical CRC cards anymore. That is why the idea of a digital table is dismissed.

The Cards: The next element to discuss is the CRC card. First, we will look at the card base. We can make it either digital or physical. This has rather strong implications on the lines and text on the card, as these depend on the card base. In case we realize it in a digital form, it will be difficult to make the lines and text on a card physical. If we have letters made of carton, we can not move them easily when the digital base of the card is moved. So once a card's medium is chosen to be digital, for practical reasons we get a purely digital CRC card including its content. In the case a card's base is physical, we get more options on how the

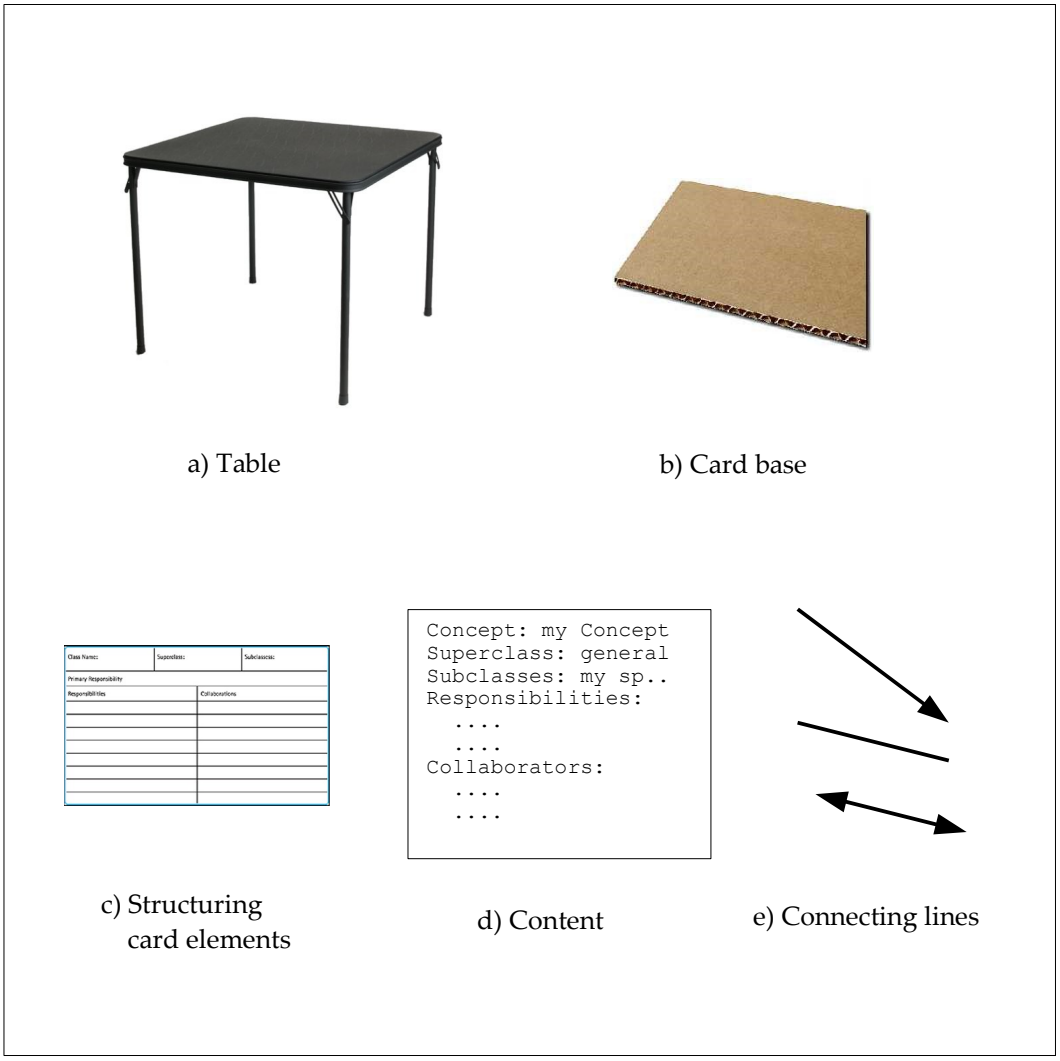


Figure 6.3: Elements for a mixed CRC cards application

card's structure and content is realized. By variating the digitality and physicality of both the cards structuring layout and the text content we get four cases. When both of them are physical, we get a purely physical card as in the classical CRC use case. The combination of a digital structure that projected onto a card and a content that is written onto it does not seem to be very wise. On the one side the content has no digital form, so it can not be used for further information processing. On the other side, when the augmenting system is not being used, the card is hard to read and interpret with the lines and helping information missing. This is an example of bad augmented reality application design, as it does not take advantage of the extended possibilities of having both digital and physical components. The last two combinations both provide digital content. The structure is either digital or physical. Both variants are taken into closer consideration. Table 6.1 gives an overview of the CRC cards, that can be tested with the application.

	Physical card	Digital card	Augmented card 1	Augmented card 2
Carrier of card	Physical	Digital	Physical	Physical
structure layout	Physical	Digital	Physical	Digital
Content	Physical	Digital	Digital	Digital

Table 6.1: Different kinds of practicable CRC cards

The connecting lines are not foreseen in the original concept or CRC cards. However, they can provide a useful extension by making the dependencies among the cards visible. For cards with digital content, the connecting lines can be found automatically and a digital connecting line be created. We could also think of materializing the connector lines, for example, as strips of paper or as a piece of string.

Result: We have now analyzed the single components. Table 6.2 shows which of them are realized digitally and which ones physically.

	Physical	Digital
Table	X	
Card's body	X	X
structure layout	X	X
Content	X	X
Card connections		X

Table 6.2: Objects of the CRC cards application and their realization

6.4.2 Ideas for an Integration of Heterogeneous CRC Cards

Redundant objects: A possibility, which we did not speak of so far, deals with redundant components in which an object exists in both a physical and a digital form at the same time. For example, we might have cards where the content is edited digitally and physically. Then we would have the cards even when the augmenting application is switched off. On the other side digital connecting lines could be augmented to the scene while the program is running. However, this overhead in digital and physical objects requires much additional work, as every edit has to be done twice, physically and digitally. If this is not done, inconsistencies can happen. In practice, users often do not perform redundant work. In a creative process supported by CRC cards, people will rather try out things in one medium and will forget to complete the task in the other medium.

Different card types in one application: Regarding the CRC cards, we have to decide whether the application is specifically designed for only one card type of table 6.1 or whether

various kinds of card types can be used. Allowing more of these types can rise the complexity of a program considerably. Not only the various card types have to be implemented, but the number of types of depending objects will also rise, probably in a nonlinear way. If we realize the two different augmented and the digital card types in table 6.1 and want the connecting lines to be realized as directed edges, we get $3 \times 3 = 9$ different kinds of connections. In our case, we know that all connecting lines can be realized as digital objects. With a reasonable software design, the different kind of cards will have the same interface for creating a connection. But in general, this is not always the case. For instance, if physical cards are connected with physical strings, and digital cards with digital edges, it is not clear how to connect a physical with a digital card. A separate solution for this case has to be found and implemented.

Another disadvantage of using different card types is that the information on the cards is not in a consistent form. The methods for manipulating and editing are different and the disparate impression to the user may cause a preference for one card type though the cards' content is of similar importance.

Despite the additional complexity of allowing multiple kinds of cards, there are also advantages. For example, let us assume that CRC cards are used collaboratively, and the participants should prepare some ideas on the project in advance. Maybe one person has a CRC card software on his computer where he can create digital CRC cards. A second person has no computer and prepares some physical cards and finally a third person uses the augmented reality application, where the later work is done in common. The single users can work in their favorite medium. In this case, heterogeneous systems exist beforehand. Additional flexibility for the users is achieved this way. The ability of augmented reality technology to integrate digital and physical objects helps to reach this goal.

Cards with mixed content: We could think of an even more heterogeneous application. One card could contain digital and physical content. One user who has no device for entering digital content could simply write onto the card whereas other users could enter digital content. This allows the highest flexibility, though it faces some difficulties: the content is highly fractionated. The models realized with the CRC cards can not be directly used without the augmented reality application, neither the physical cards nor the digital parts. If a card can not be tracked for some reason — what happens frequently — the physical and the digital content are separated. Due to that, such cards with mixed content were not used within this work.

6.5 Details on the Implemented CRC Cards Application

We will now describe the features of the realized CRC card program. Several of the aforementioned features could be tested and evaluated.

First we want to shortly describe the used technologies. For tracking the ARToolkit was used. The video capture was done with a Logitech Pro 400 video camera, though many other video cameras can be used with the ARToolkit. The software can run with two different set–ups. For the first set–up, a computer monitor is used. The video image that is also used for tracking the ARToolkit markers, is displayed on the screen and overlaid by the digital

objects (see figure 6.5). As the augmentations can not be seen on the real object in the users' view, but just on the video image, this is a pseudo augmented reality application. However, in this way, it can be tested easily. In the second set–up the camera just works as tracker. It is located below the table, which is a Plexiglas plate (see figure 6.4). The augmentations onto physical objects are performed by a video projector. In order to view the digital CRC cards, we have to lay some piece of paper on the table, because on the glass they can not be seen.

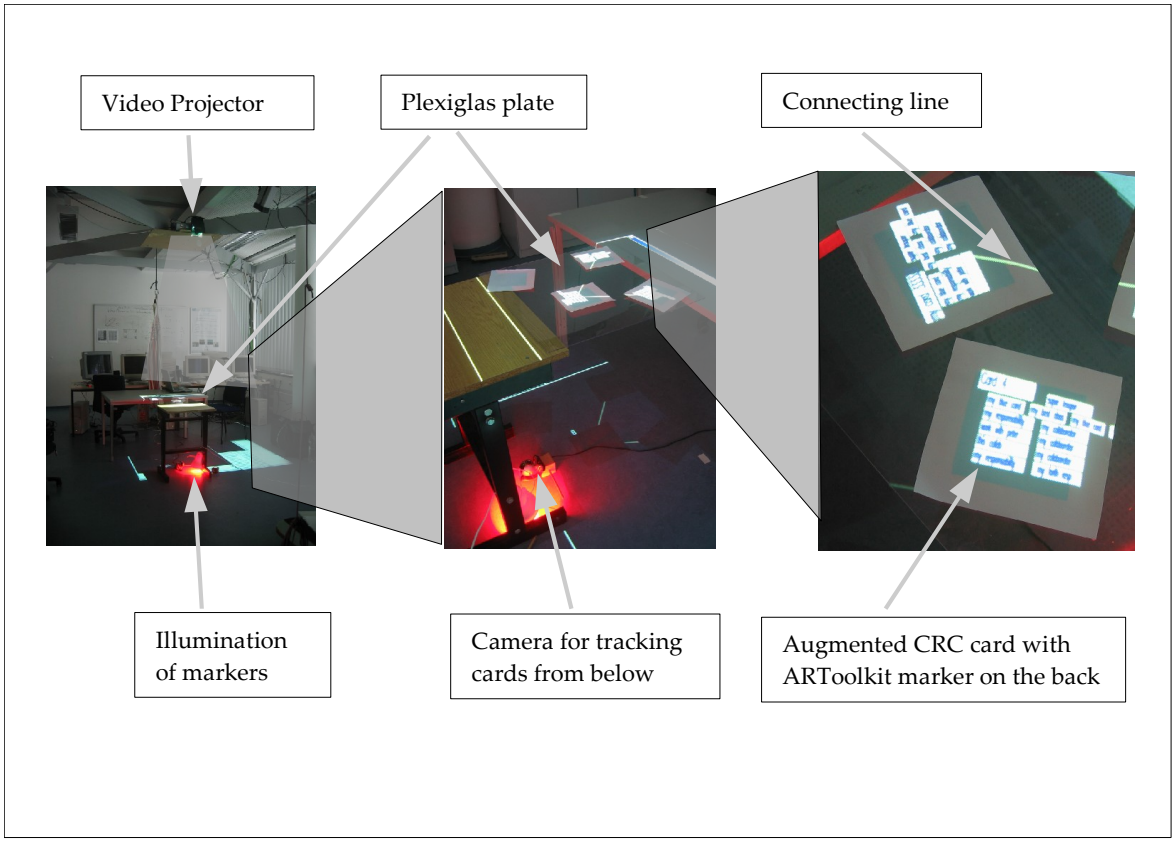


Figure 6.4: The CRC cards application in video projector mode

Several aspects discussed before could be realized:

Physical Cards: Of course physical CRC cards can be used. However, they are not tracked. That is why neither their position is known nor their content.

Digital Cards: The application supports digital CRC cards. These cards are displayed some location in space. In case the video projector is used. The digital cards can be moved in space using the keyboard. Furthermore, the content can be entered or modified. The cards can also be made invisible. Figure 6.5 shows the digital CRC cards in red color.

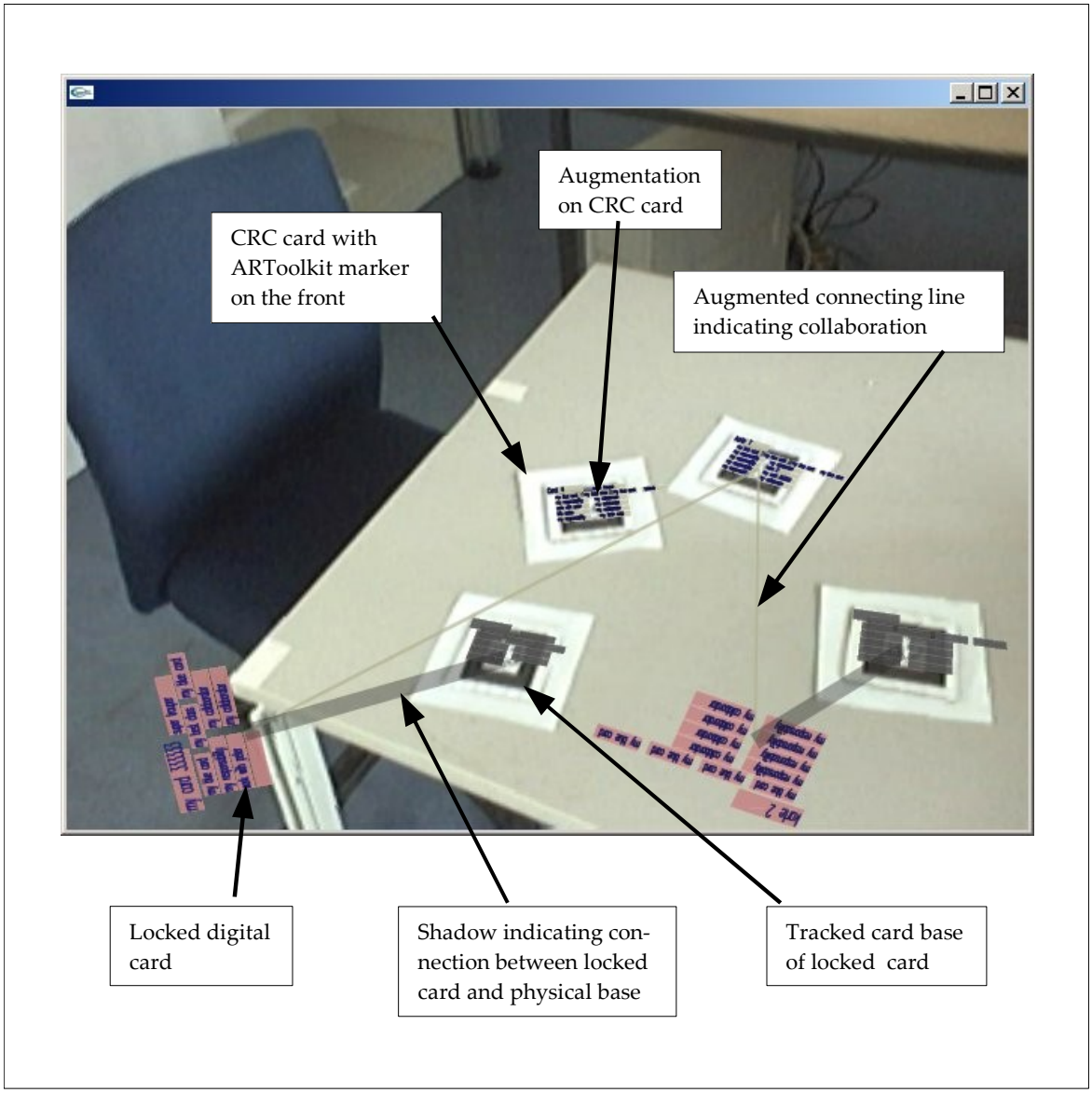


Figure 6.5: The running CRC card application

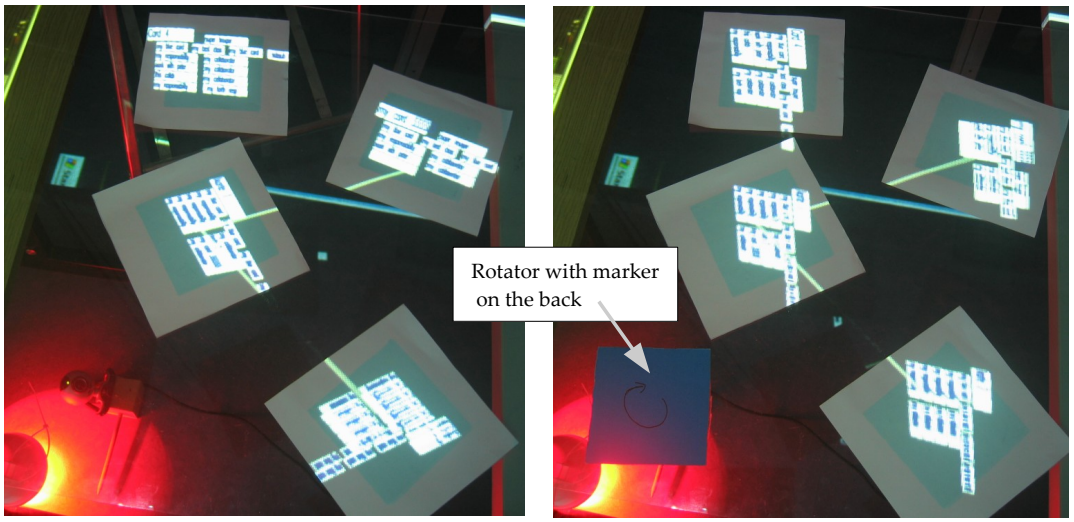
Augmented Cards: Augmented CRC cards can be used. The content of the augmented cards is always digital and can be edited like the digital card. The position the augmented cards is tracked and known to the application that projects the augmentations onto the physical cards. Two versions of them with and without the scheme printed on it were tested. However, the tracking does not work so exactly that the content always matches the correct fields of the card. Figures 6.4 and 6.5 both show in a light yellow color.

Connecting Lines: The digital connecting lines are drawn automatically as soon as a collaboration of two cards is discovered and both cards are visible. There is no difference

whether the card is digital or augmented.

Also some additional things realized. They should show a few of the many ideas on digital and mixed objects mentioned in chapter and 3 and 4:

Rotator: When collaborative work around the table is done with the CRC cards, not everybody will see the cards from the same perspective, but from the side or even upside down. The rotator — a simple ARToolkit marker — can modify the orientation of all digital and the digital parts of the augmented cards (see figure 6.6). As long as the rotator is tracked, every of them adopts the orientation that the rotator provides. Also when the cards are messy, their orientation can be aligned by the rotator. This is another reason why the structure printed physically on the augmented cards is not favorable. The structure would not correspond at all with the projection of the content.



a) Scene with arbitrarily oriented cards

b) Scene with aligned orientation of cards using a rotator

Figure 6.6: Synchronous rotating of CRC cards

Digitization of augmentations: Tracking of single CRC cards is often disturbed. Sometimes the light conditions are not appropriate, sometimes a card hides the marker of another

card, sometimes a card's tracker is partially out of the camera's sight. The application turns the augmented cards into a digital cards as long as it is not tracked. When they are tracked again, they instantly turn into augmented cards. Figure 6.7 shows this process.

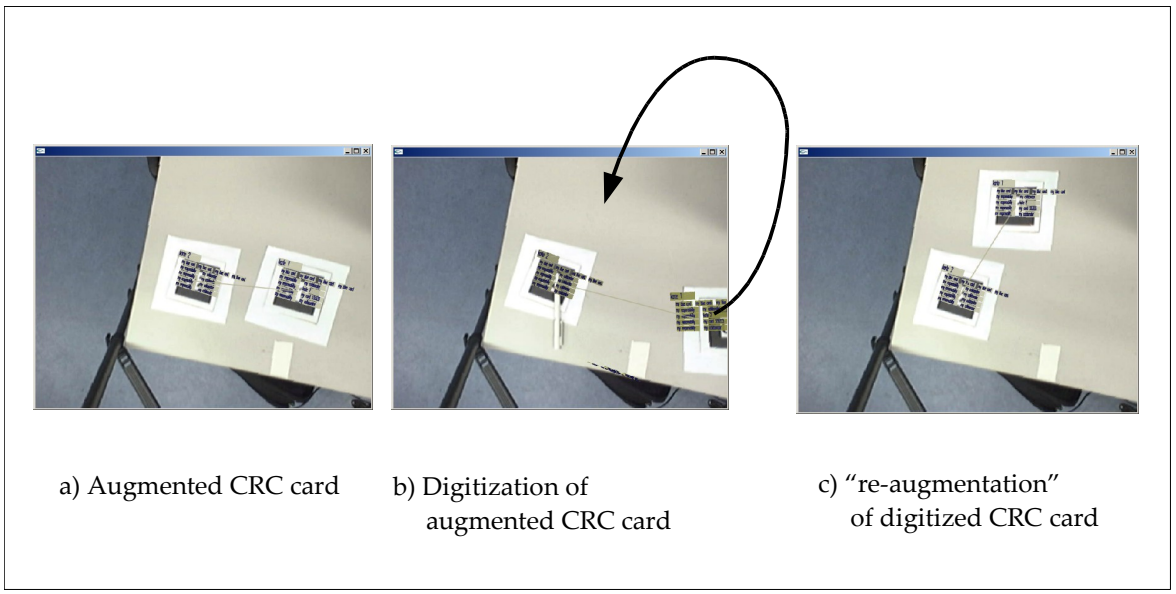
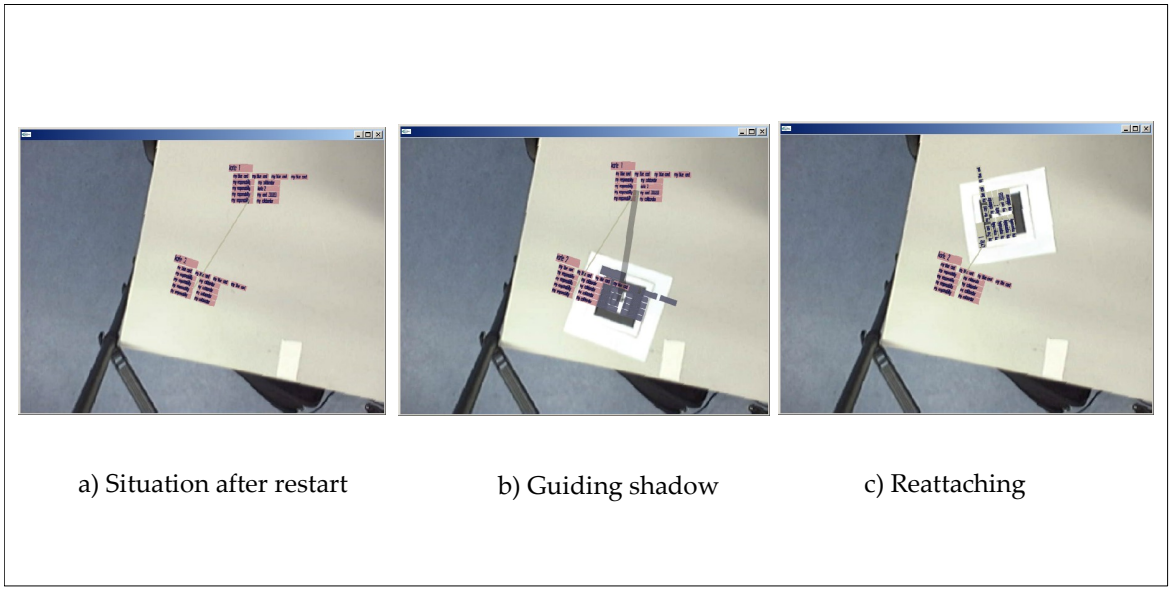


Figure 6.7: Digitization of augmented CRC cards

Saving: When the application is terminated, all the content on the digital and augmented cards, as well as the cards' last position and orientation is saved. The modifications done by the rotator are ignored, however. The work can be continued later, or other programs could use the text files that contain the content. The physical cards, however, can not be saved.

Reload of the application: When the application is started, it is tried to restore the last state of the CRC cards. There might be the problem, though, that the cards are not at the position they were when the program was terminated. Maybe they are not visible at all. Or the cards were temporarily removed from the table, but their previous position is unknown. However, the previous location and grouping might be important for a better orientation. In order to achieve that, all cards are realized as digital cards on start–up. When the physical part of a previously augmented card is tracked, the augmentation does not appear on the card, before we know, where the digital parts previously were. Instead the connection will be indicated by a shadow, linking the physical part with the augmentation. That way the user knows which parts belong together. Not until both cards come close to each other, the digital card disappears and its content is reattachment as to its physical counterpart. This process can be seen in figure 6.8.



a) Situation after restart b) Guiding shadow c) Reattaching

Figure 6.8: Reattachment of augmentations on restart

6.6 Outcome of the CRC Cards Application

In the following, the new insights will be described that could be gained from testing the CRC card software. We will see, how the different alternatives of CRC cards performed.

CRC cards can be manipulated by moving them or by editing its content. In the case of moving the cards, we have most freedom in using the physical cards. We can even put them outside the space that is used for the application. The only limitations are that they can not hover in space; so we are limited to the table plane if we do not lift a card with our hands. The digital cards can be moved with the keyboard. This is not very intuitive. The augmented cards can be moved much like the physical cards. However, they are restricted to the space that the tracking system can oversee. When they are out of it, an augmentation can not be performed. The aforementioned "digitalization" of augmented cards that are out of sight, minimizes that problem.

Editing works rather well for physical cards, for digital and augmented cards. The users can just take a card and write something on it. Entering information is quite cumbersome. A card has to be chosen, then a field, and finally the content be entered using the keyboard.

The connecting lines can be drawn automatically for augmented and digital cards. This has shown to be very helpful. With the physical cards you have to real all connector fields in order to find the dependencies.

Collaborative work can be done well for physical cards. The users can move cards and write something on them even concurrently. This is contrary to digital cards. As the application only runs on one PC and only supports one keyboard, the digital cards can only be manipulated by the user who controls the PC. This does not support collaboration very much. The situation is somewhat better with the augmented cards. The users can move the cards independently from each other. However, the entering of content can not be done concurrently.

Save and restart: Regarding the continuing of the work restart application. Physical cards, we get problems to reorganize them as they were previously. In a digital application, this is no problem, as the exact state can be saved and reconstructed. More complicated for augmented cards, physical cards: information lost. order (order after save state)

The rotator has shown to be quite helpful. Of course, it does not work with physical cards. In connecting the augmented and also the digital cards to it we can achieve a good integration of augmented and digital objects in this point.

Results: We can say that augmented cards really have advantages over both physical and digital cards. We have to keep in mind, though, that such an augmented reality application is designed properly. For the single components and their connections a the form has to be chosen that provides most advantages for the later use. Table 6.3 summarizes the findings and concludes this chapter.

	Physical CRC cards	Digital CRC cards	Augmented CRC cards
Moving around CRC cards	Move freely	Cumbersome keyboard control	Move freely within tracking area
Editing content	Easy	Cumbersome keyboard control	Cumbersome keyboard control
Overwriting Content	Difficult	Possible	Possible
Connecting lines	Only manually	Automatically	Automatically
Collaborative work	Works well	Disadvantages	Less disadvantages
Restart work	Cumbersome reconstruction	Perfect	Assistance in restart
Rotator	Not applicable	Helpful	Helpful
Automatic processing of content	No	Possible	Possible

Table 6.3: Evaluation of CRC cards application

7 Summary and Outlook

7.1 Summary

The intent of this thesis was to provide a more general understanding of digital, physical, and mixed objects.

Characteristics of physical objects were analyzed and their impact explained. We could see that the simulation of physical objects can be achieved for most characteristics, but only partially and with restrictions. Todays computers can only reproduce a small fraction of our real world. Also future computers will not change that.

Next we focused on specific characteristics of digital objects. Although often derived from the real world, new concepts have evolved in computer science like access rights, copying of information, and more general new forms of data manipulation. These concepts were described and their usefulness was illustrated. Furthermore, we analyzed ways to apply these digital concepts to physical objects. Often this concepts can be achieved by creating active physical objects. These objects can contain actuators like motors as well as integrated displays and sensors.

With the findings of similarities and differences of digital and physical objects, we evaluated the possibilities of linking them to mixed objects. We could find a lot of forms of different connections. It could be shown that there are more possibilities in augmented reality than just displaying some objects or additional information. By going through all these possibilities we can do a more systematic approach in designing mixed objects. This was demonstrated in the design of a CRC cards application.

We also showed how collaboration works in physical and digital worlds. Several differences could be identified. Finally, new ways of collaboration in mixed worlds were analyzed. Augmented collaborative work seems to have a large potential especially with applications for conference tables. Here, the CRC card example tried to demonstrate that the efficiency of collaborative work can be optimized by choosing components either to be realized as physical or digital objects. Also telecollaboration in augmented reality was discussed. We saw that completely new ways of collaboration can be achieved by the increased possibilities of realizing either physical, digital, or mixed objects.

7.2 Augmented Reality in the Future

Augmented reality could play a major role in very different domains. There are already a few areas where augmented reality is used frequently. Most fields are to be developed in the future, when new fields of application are found and when the technology behind augmented reality has improved. We will now name some of such existing and possible future areas and find out where the knowledge of this work might be of use.

Unpredictability of augmented reality development: However, the development is difficult to predict. We can not know for sure in which areas of our live augmented reality will enter. Will it soon enter the consumer market, or will it primarily be used in industry, or will it remain in a niche at research institutions for a longer time? The question is also which of these areas will be conquered first. Even more unpredictable is, which kinds of applications will bring the break through for augmented reality technology. Take the development of the computer, for example. It was originally designed for doing calculations. Today, however, most people do all kinds of things with the computer except for calculations. It is primarily used for writing, painting, communicating, finding information on the internet, listening to music, watching videos and so on. Of course all software is processed by the computer's CPU and by doing so it is eventually lead back to a calculation. For the user the mathematical calculations are hidden.

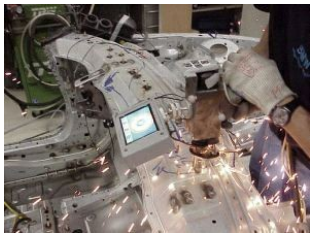
Despite this unpredictability it makes sense to think about future markets of augmented reality technology. First, we want to see where this technology is already in the developing.

Automotive sector: In the automotive industry augmented reality will probably be used for prototyping. The Fraunhofer-Institut für Graphische Datenverarbeitung already worked on a rapid product development software for augmented reality (see figure 7.1a and [21]). As for different prototypes different parts are made physically, augmented reality could augment the parts not modeled physically even in early stages of development or in partial prototypes. Also new kinds of prototypes with a new distribution of physical and digital parts can be thought of. As prototyping allows a great flexibility in deciding on either digital or physical parts, a lot of ideas covered in this thesis can be applied. It provides a vast range of alternatives on how each parts of a prototype is realized and how the parts can be connected.

Other areas on the automotive industry are evaluated, including production (see figure 7.1b and [12]). It is also discussed how augmented reality can be integrated into the car, so that it supports driving. The augmentations could be realized by projecting them onto the car's front window (see figure 7.1b and [55]), or by directly integrating liquid crystals into the glass. Not only information about the state of the car could be displayed, but the view of the driver could be analyzed and augmented. A zebra crossing, for example, could be recognized and marked in the view. The main task of the system is to recognize physical objects on or near the street and attach augmentations to them. Here, especially the possibilities of connecting the recognized physical objects with the augmenting digital objects as described in chapter 4 could be of use.

Medical Area: Augmented reality in the medical branch is also heavily researched, especially in operating room. The (internal) parts of the body that are to be diagnosed or operated, can be augmented onto the patient's body (see figure 7.2a–b, [35], and [48]). Main fields of research deal witch tracking a human body and medical instruments, as well as generation of the augmentations from x–ray and other data from and overlay. The separation of digital and physical parts can not be changed, as the body and the instruments are necessarily physical and the images have to be projected into the doctors view and, hence, are digital. Furthermore, it is important to be always able to differ between the augmentations and the human body, what does not permit a too perfect optical integration of physical and digital objects. Consequently, for today's operations the results of this work only play

a) Prototyping (Fraunhofer)



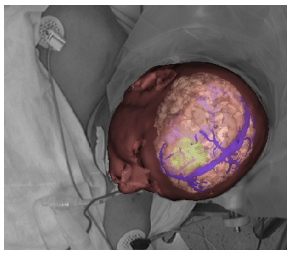
b) Production

c) Head-up display for cars

Figure 7.1: Augmented reality in the automotive industry

a minor role. For telemedicine (7.2d), however, also other scenarios can be thought of. In the future, a doctor could do an operation on a remote physical body by performing his actions on a local digital body. Another field where this study's results could be applied is the teaching and training of operations. Depending on the kind of operation to be taught and quality of artificial physical body parts available, digital and mixed objects could improve traditional trainings on physical bodies.

Non–commercial applications: Also non–commercial projects deal with augmented reality. The advantage here is that the applications are mostly non–critical and offer a great



a) Diagnosis

b) Operation

c) Telemedicine

Figure 7.2: Computer aided medicine

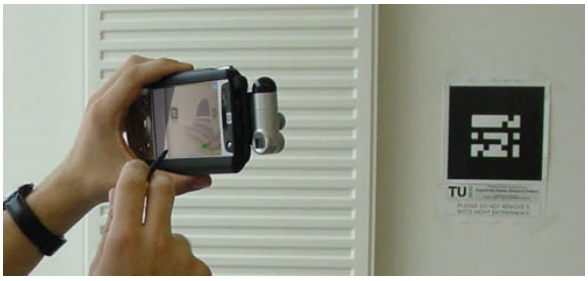
flexibility in applying new technologies, which allows to think of realizing also the more exotic ideas presented here. Museums are quite interested in unusual presentation of their exhibits. Further non–commercial examples are two augmented archeology projects, one is done under Steven Feiner at Columbia University [17], the other one is a European research project called ARCHEOGUIDE [1].

Consumer products: Electronic game industry has considerably helped to improve a lot of technologies including the performance of the PC, especially its computer graphic skills. A playful approach has helped many technologies on the road to success. This could also boost augmented reality. We have discussed an augmented chess game in chapter 4. Since mobile devices are increasingly equipped with cameras, they could be used for augmented reality. There are even the first mobile games that use this technology: the game "Mosquito Hunt" (see [54]) works on mobile phones and shows some digital mosquitoes. As background the images of the integrated camera are used. When the mobile phone is moved, also the mosquitoes are moved, so that they remain on the same place related to the background. Also digital camera and PDAs will increasingly contain cameras. There are various augmented PDA projects, for example at Studierstube (see [58]. This potential should be used, and some ideas of this work could be used.

7.3 Future work and Outlook

This work provided a rather theoretic approach. The advantages and disadvantages of physical, digital and mixed objects were analyzed; their assessment was based merely on logic reasoning and assumptions. When human beings use new technologies, the theoretical ad-

a) “Mosquito Hunt” on mobile phone



b) Augmented reality on PDA

Figure 7.3: Augmented reality in consumer products

vantages are not always fulfilled to the prospected degree, though. Human beings perceive digital and physical objects differently, some people use to avoid certain technologies or show less performance for some reason. For example, some people tend to write more quickly on paper, others writer more quickly with a keyboard. This is due to the fact that some feel freer on paper — as they can do graphics, write exotic letters, perform markings, etc. — others feels more freedom on the computer — as they can reedit everything and write in an highly non–linear way.

Because of that, the theory provided here can not be used unrestrictedly. Augmented reality systems have to be tested, if they really provide the improvements they promised. Furthermore, user studies have to be done. Human–computer interaction explores how humans deal with computers and tries to improve this relationship. What Wendy Mackay [14] explored for the work with paper in augmented reality, can be applied to other areas of augmented reality.

A lot of further research can be done in order to find out, if, where and how augmented reality can be applied successfully. This thesis is one piece of that work.

Bibliography

[1] ARCHEOGUIDE, *Augmented Reality–based Cultural Heritage On-site Guide*. *http://archeoguide.intranet.gr/project.htm*.

[2] A.R.T GMBH, *Homepage of A.R.T. http://www.ar-tracking.de*.

[3] ARTOOLKIT, *ARToolKit and Download and Page*. *http://www.hitl.washington.edu/research/shared_space/download/*.

[4] ARVIKA CONSORTIUM, *Homepage of the ARVIKA project*. *http://www.augmented-reality.de*.

[5] K. BECK and W. CUNNINGHAM, *A Laboratory For Teaching Object-Oriented Thinking*, in OOPSLA'89 Conference Proceeding, 1989.

[6] B. A. BELL, S. K. FEINER, and T. HÖLLERER, *View Management for Virtual and Augmented Reality*. *http://www1.cs.columbia.edu/graphics/projects/ViewManagement/index.html*.

[7] M. BENALI-KHOUDJA, M. HAFEZ, J.-M. ALEXANDRE1, J. BENACHOUR, and A. KHEDDAR, *Thermal feedback model for virtual reality*, CEA LIST SRSI, Laboratoire Systemes Complexes – University of Evry, France.

[8] M. BERGAMASCO, *Shape Perception of 3D Virtual Objects by Tactile Feedback Systems*, PERCRO, Scuola Superiore S. Anna, Pisa, Italy. http://www.ercim.org/publication/Ercim_News/enw31/bergamasco.html.

[9] I. BRONSTEIN, K. SEMENDJAJEW, G. MUSIOL, and H. MÜHLIG, *Taschenbuch der Mathematik*, Verlag Harri Deutsch, 1999.

[10] B. BUXTON, *Homepage of Bill Buxton. http://www.billbuxton.com*.

[11] DUDEN, *Duden Informatik — Ein Fachlexikon für Studium und Praxis*, Dudenverlag, Mannheim, 2001.

[12] F. ECHTLER, F. STURM, K. KINDERMANN, G. KLINKER, J. STILLA, J. TRILK, and H. NAJAFI, *The Intelligent Welding Gun: Augmented Reality for Experimental Vehicle Construction. http://wwwnavab.in.tum.de/Chair/ProjectPaarti*.

[13] EDGELAB, DALHOUSIE UNIVERSITY, CANADA, *Tabletop Displays as Collaborative Interfaces. http://www.edgelab.sfu.ca/projects/merl_description.html*.

[14] W. E.MACKAY and A.-L. FAYARD, *Designing Interactive Paper: Lessons from three Augmented Reality Projects*, in Proceedings of IWAR98, International Workshop on Augmented Reality, 1998. *http://www-ihm.lri.fr/~mackay/publications.html*.

[15] O. FAUGERAS, *Three–Dimensional Computer Vision*, The MIT Press, Cambridge, Mass., 1993.

[16] S. FEINER, *Computer Graphics & User Interfaces Lab at Columbia University*. *http://www1.cs.columbia.edu/graphics/top.html*.

[17] S. FEINER, E. ISHAK, and H. BENKO, *Collaborative Visualization of an Archaeological Excavation*. *http://www1.cs.columbia.edu/graphics/projects/ArcheoVis/index.html*.

[18] G. W. FITZMAURICE, H. ISHII, and W. BUXTON, *Bricks: Laying the Foundations for Graspable User Interfaces*, in Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'95), 1995, pp. 432–449. *http://www.billbuxton.com/bricks.html*.

[19] M. FJELD, *Homepage of Morton Fjeld*. *http://www.fjeld.ch/*.

[20] M. FJELD, F. VOORHORST, M. BICHSEL, H. KRUEGER, and M. RAUTERBERG, *Navigation Methods for an Augmented Reality System*, in In the video program / extended abstracts of CHI 2000, 2000.

[21] FRAUNHOFER-INSTITUT FÜR GRAPHISCHE DATENVERARBEITUNG, *Rapid Product Development durch Verbindung von virtuellen und physikalischen Modellen*. *http://www.igd.fhg.de/igd-a2/projects/MixedRealityAP/index.html*.

[22] E. GAMMA, R. HELM, R. JOHNSON, and J. VLISSIDES, *Design Patterns – Elements of Reusable Object–Oriented Software*, Addison-Wesley, 1995.

[23] H. HOFFMAN, J. GROEN, S. ROUSSEAU, A. HOLLANDER, W. WINN, M. WELLS, and T. FURNESS, *Tactile Augmentation: Enhancing presence in virtual reality with tactile feedback from real objects*, 1996.

[24] HUMAN INTERFACE ENGINEERING LABORATORY, OSAKA UNIVERSITY, *Virtual Tools, Virtual Hand — Virtual Chopstics*. *http://www-human.ist.osaka-u.ac.jp/VirtualTools/*.

[25] IBM RESEARCH, *PRAVDA: Perceptual Rule-based Architecture for Visualizing Data Accurately — Different colormaps impart different meanings*. *http://www.research.ibm.com/dx/imageGallery/pravda.html*.

[26] IDF — THE INTERNATIONAL DOI FOUNDATION, *What is UUID?* *http://www.dsps.net/uuid.html*.

[27] H. ISHII, *Homepage of Hiroshi Ishii*. *http://web.media.mit.edu/~ishii/*.

[28] H. ISHII and B. ULLMER, *Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms*, in CHI 2000 Proceedings, 1997.

[29] G. KLINKER, *Augmented Reality Page of Prof. Grudrun Klinker, Ph.D.* *http://ar.in.tum.de/Chair/AugmentedReality*.

[30] G. KLINKER, H. NAJAFI, T. SIELHORST, F. STURM, F. ECHTLER, M. ISIK, W. WEIN, and C. TRÜBSWETTER, *FixIt: An Approach towards Assisting Workers in Diagnosing Machine Malfunctions*. *http://wwwnavab.in.tum.de/Chair/ProjectFixit*.

[31] LENNARTZ ELECTRONIC, *MOdular SEnsor System, IInd generation*. *http://www.lennartz-electronic.de/Pages/MOSES/MOSES_home_e.html*.

[32] LEO DICTIONARY TEAM AT THE DEPARTMENT OF INFORMATIK, TECHNISCHE UNIVERSITÄT MÜNCHEN, *LEO — a german–english online dictionary*. *http://dict.leo.org*.

[33] L. L. LIPP, *Interaktion zwischen Mensch und Computer im Ubiquitous Computing*, LIT–Verlag, 2004.

[34] W. MACKAY, *Augmenting paper flight strips for air traffic control*. *http://www-ihm.lri.fr/m̃ackay/posterA.html*.

[35] MEDARPS, *MEDical Augmented Reality for PAtients*. *http://www.medarpa.de/*.

[36] MICROSOFT CORCOPRATION, *MSDN library — C++ Language Reference*. *http://msdn.microsoft.com/library/default.asp?url=/library/en-us/vccelng/htm/plintro.asp*.

[37] P. MILGRAM and H. COLQUHOUN JR., *A Taxonomy of Real and Virtual World Display Integration*, in International Symposium on Mixed Reality, ISMR99, 1999.

[38] MIT MEDIA LABORATORY. *http://tangible.media.mit.edu/*.

[39] M. R. MORRIS, *Designing Tabletop Groupware*, in UIST 2005 Doctoral Symposium, 2005.

[40] N. NAVAB, *Computer Aided Medical Procedures (CAMP)*. *http://wwwnavab.in.tum.de/view/Chair/ResearchCamp*.

[41] Y. OHTA and H. TAMURA, *Mixed Reality — Merging Real and Virtual Worlds*, Ohmsha, Ltd. & Springer–Verlag, Tokyo, Japan, 1999.

[42] E. OKEN, *Illustration of scene design on "Little Village Far, Far Away"*. *http://www.oken3d.com/html/image56.html*.

[43] OPENGL ARCHITECTURE REVIEW BOARD, M. WOO, J. NEIDER, T. DAVIS, and D. SHREINER, *OpenGL programming guide: the official guide to learning OpenGL, version 1.2*, Addison–Wesley, Reading, Massachusetts, 3rd ed., 1999.

[44] H. PARK and J.-I. PARK, *Invisible Marker Tracking for AR*. Department of ECE, Hanyang University Seoul, Korea.

[45] A. POWELL, *Unique Identifiers in a Digital World*. *http://www.ariadne.ac.uk/issue8/unique-identifiers/*.

[46] J. PREECE, *Human–Computer Interaction*, Addison–Wesley Publishing, 1994.

[47] N. ROBINS, *Homepage of GLUT for Win32*. *http://www.xmission.com/∼nate/glut.html*.

[48] UNIVERSITY OF ROCHESTER, *Medical Augmented Reality*. *http://www.cs.rochester.edu/u/brown/Images/brain_ar.gif*.

[49] K. SCHÄFER, *Real Reality — Simulationsunterstützung durch gegenständliche Modelle*, in Simulation und Visualisierung, SCS, Magdeburg, 1998.

[50] D. SCHMALSTIEG, *Publications of Dieter Schmalstieg*. *http://www.icg.tu-graz.ac.at/ICG/Members/schmalstieg//index_html*.

[51] B. SHNEIDERMAN, *Designing the User Interface*, Addison–Wesley Publishing, 1997.

[52] SILICON GRAPHICS INC., *OpenGL hompage. http://www.opengl.org*.

[53] SIEMENS, *FET gas sensors for detecting smell. http://www.physorg.com/news1194.html*.

[54] SIEMENS, *Virtual Mosquito Hunt for Cell Phones, Cebit 2003*. *http://w4.siemens.de/en2/html/press/newsdesk_archive/2003/foe03111.html*.

[55] SIEMENS VDO, *Siemens VDO Automotive Head Up Display (HUD) fro BMW*. *http://www.usa.siemensvdo.com/media/images/ii/list.htm*.

[56] A. SONG, *Hand-controller with force and tactile feedback*. *http://lims.mech.northwestern.edu/students/song/*.

[57] B. STROUSTRUP, *Die C++ Programmiersprache*, Addison–Wesley, Boston, Mass., 2000.

[58] STUDIERSTUBE AUGMENTED REALITY PROJECT, *Handheld Augmented Reality AR on truly Mobile Devices. http://studierstube.org/handheld_ar/*.

[59] STUDIERSTUBE AUGMENTED REALITY PROJECT, *Project Homepage of Studierstube*. *http://studierstube.org/*.

[60] W. STUERZLINGER, *MULTI: Multi–User Laser Table Interface*, York University, Toronto, Canada.

[61] VISUAL PARADIGM, *CRC Card Diagram in "Visual Paradigm for UML"*. *http://www.visual-paradigm.com/VPGallery/diagrams/CRCCard.html*.

[62] V. VLAHAKIS, J. KARIGIANNIS, and N. IOANNIDIS, *Augmented Reality Touring of Archaeological Sites with the ARCHEOGUIDE System*, Cultivate Interactive. *http://www.cultivate-int.org/issue9/archeoguide/*.

[63] WEBNOX CORPORATION, *hyperdictionary — an online dictionary*. *http://www.hyperdictionary.com*.

[64] WIKIPEDIA, *Wikipedia — The Free Encyclopedia. http://www.wikipedia.org*.

[65] C. ZENGER, H.-J. BUNGARTZ, and GRIEBEL, *Einführung in die Computergraphik*, Vieweg Verlag, 1996.