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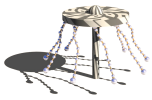

New Game Physics

Added Value for Transdisciplinary Teams

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Abstract

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This study focused on game physics, an area of computer game design where physics is applied in interactive computer software. The purpose of the research was a fresh analysis of game physics in order to prove that its current usage is limited and requires advancement. The investigations presented in this dissertation establish constructive principles to advance game physics design. The main premise was that transdisciplinary approaches provide significant value. The resulting designs reflected combined goals of game developers, artists and physicists and provide novel ways to incorporate physics into games. The applicability and user impact of such *new game physics* across several target audiences was thoroughly examined.

In order to explore the transdisciplinary nature of the premise, valid evidence was gathered using a broad range of theoretical and practical methodologies. The research established a clear definition of game physics within the context of historical, technological, practical, scientific, and artistic considerations. Game analysis, literature reviews and seminal surveys of game players, game developers and scientists were conducted. A heuristic categorization of game types was defined to create an extensive database of computer games and carry out a statistical analysis of game physics usage. Results were then combined to define core principles for the design of unconventional *new game physics* elements. Software implementations of several elements were developed to examine the practical feasibility of the proposed principles. This research prototype was exposed to practitioners (artists, game developers and scientists) in field studies, documented on video and subsequently analyzed to evaluate the effectiveness of the elements on the audiences.

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The findings from this research demonstrated that standard game physics is a common but limited design element in computer games. It was discovered that the entertainment driven design goals of game developers interfere with the needs of educators and scientists. Game reviews exemplified the exaggerated and incorrect physics present in many commercial computer games. This "pseudo physics" was shown to have potentially undesired effects on game players. Art reviews also indicated that game physics technology remains largely inaccessible to artists. The principal conclusion drawn from this study was that the proposed *new game physics* advances game design and creates value by expanding the choices available to game developers and designers, enabling artists to create more scientifically robust artworks, and encouraging scientists to consider games as a viable tool for education and research. The practical portion generated tangible evidence that the isolated "silos" of engineering, art and science can be bridged when game physics is designed in a transdisciplinary way.

This dissertation recommends that scientific and artistic perspectives should always be considered when game physics is used in computer-based media, because significant value for a broad range of practitioners in succinctly different fields can be achieved. The study has thereby established a state of the art research into game physics, which not only offers other researchers constructive principles for future investigations, but also provides much-needed new material to address the observed discrepancies in game theory and digital media design.

Keywords: *game physics, computer game design, transdisciplinary studies, digital art*

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March 11, 2012

Contents

Executive Summary **xi**

List of Figures **xiii**

List of Tables **xv**

1 Introduction **1**

2 Game Physics **9**

2.1 Introduction 9

2.2 Physics and Context for Research 10

2.3 Standard Game Physics 11

2.3.1 Game Physics as Design Element 11

2.3.2 Types of Game Physics 14

2.3.3 Numerical Models and Simplifications 24

2.3.4 Trends in Game Physics 26

2.4 Pseudo Game Physics 35

2.4.1 Limited Field-Coverage 36

2.4.2 Lack of Precision 39

2.4.3 Physical Hyperreality 42

2.4.4 Movie Physics 44
2.5 Perspectives on Game Physics 47
2.5.1 Interviews with Game Developers 49
2.5.2 Game Player Survey 60
2.5.3 Physicists Survey 69
2.6 Chapter Conclusion 74

3 Quantitative Analysis 78

3.1 Introduction 78
3.1.1 Validation of Methodology 79
3.1.2 Influences of Technological Advances 79
3.2 Categorizations of Computer Games 81
3.2.1 Existing Taxonomies 83
3.2.2 Proposed Categories for Research 90
3.3 Game Physics Index 91
3.3.1 Object Dynamics and Spatiality 93
3.3.2 Definition and Accuracy 97
3.3.3 Assignment of Index Values 99
3.3.4 Generation of Database 99
3.4 Analysis of Game Database 104
3.5 Chapter Conclusion 115

4 Theories of Play 118

4.1 Introduction 118
4.2 Literature Reviews: Historical 119
4.2.1 Huizinga – Homo Ludens 119
4.2.2 Scheuerl – The Phenomenon of Games 124
4.2.3 Caillois – Les Jeux et les Hommes 127
4.2.4 Heckhausen – The Psychology of Play 132
4.3 Literature Reviews: Current 137

4.3.1 Juul – On Rules and Worlds . . . 137
4.3.2 Koster – Fun in Game Design . . . 143
4.3.3 Gee – Games and Learning . . . 149
4.3.4 Galloway – Algorithmic Cultures . . . 157
4.4 Chapter Conclusion . . . 162

5 Physics Elements 164

5.1 Introduction . . . 164
5.2 Designing New Game Physics Elements . . . 165
5.2.1 Principles from Science . . . 165
5.2.2 Principles from Game Physics . . . 166
5.2.3 Principles from Practitioners . . . 167
5.2.4 Principles from Quantitative Analysis . . . 168
5.2.5 Principles from Theories of Play . . . 169
5.3 Videogames and Art . . . 170
5.3.1 Can Computer Games be Art? . . . 170
5.3.2 Characteristics of Art Games . . . 171
5.3.3 Artistic Strategies in Videogame Art . . . 172
5.3.4 Summary . . . 176
5.4 Art of Science . . . 177
5.4.1 Analyzing Physics Art . . . 178
5.4.2 Selected Physics Art Examples . . . 179
5.4.3 Principles from Physics Art . . . 186
5.4.4 Summary . . . 188
5.5 Value for Artists . . . 189
5.5.1 Examples . . . 190
5.5.2 Summary . . . 197
5.6 Elements: Physics in Game Mechanics . . . 198
5.6.1 Relativity Theory and Game Time . . . 199
5.6.2 Pendulum “Flip a coin” Generator . . . 204

5.7 Elements: Physics as Game Story . . . 207
5.7.1 The Birth Cry of Atoms . . . 208
5.8 Elements: Game Aesthetics from Physics . . . 212
5.8.1 My Avatar is Chaos . . . 213
5.8.2 Fields of Charged Space . . . 218
5.9 Elements: Physics in Game Technology . . . 221
5.9.1 Physical Entropy in Computer Games . . . 222
5.9.2 Reality Blending . . . 229
5.10 Design Framework for GPEs . . . 233
5.11 Chapter Conclusion . . . 237

6 Prototypical Implementations 239

6.1 Introduction . . . 239
6.2 playtrulyrandom.com . . . 240
6.2.1 Concept and Goals . . . 240
6.2.2 HRNG Implementation . . . 241
6.2.3 Software Architecture . . . 242
6.2.4 Demonstration Game . . . 242
6.2.5 Summary and Results . . . 245
6.3 Pendulum Game . . . 246
6.3.1 Concept and Architecture . . . 246
6.3.2 Accuracy in the Game . . . 248
6.3.3 Physical Rules . . . 256
6.3.4 Game Technology . . . 260
6.3.5 Scientific Narratives . . . 264
6.3.6 Summary and Results . . . 267
6.4 Field Study . . . 267
6.4.1 Focus Groups and Physical Setup . . . 267
6.4.2 Summary of Video Documentation . . . 269
6.4.3 Observations and Results . . . 269

6.5 Chapter Conclusion 276

7 Conclusion **278**

Bibliography **289**

Glossary **315**

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Executive Summary

Current game physics is limited and requires advancement. A fresh analysis of game physics by transdisciplinary approaches is needed to advance the state of the art in the field of computer game design. Specifically, teams made up of game developers, artists and physicists can contribute to a trajectory that I call *new game physics*. The added value would develop from a multifaceted set of goals such as:

- expanding the choices available for game developers and designers
- enabling artists to create more scientifically robust artworks
- encouraging scientists to consider that games can be a viable tool for education and research

This research is guided by a clear definition of game physics within the broad context of historical, technological, practical, scientific, and artistic considerations. The study aims to overcome limitations in current game physics and demonstrate to content developers how novel cross-disciplinary approaches involving physicists and artists can provide value. This dissertation may establish a beginning to state of the art research in game physics and offer other researchers constructive principles that can be used in future investigations.

The research in this dissertation represents a new approach to game physics design, as there has been little prior artwork or publications in this domain with a transdisciplinary agenda. The context in which game physics is placed in this study therefore directly constitutes the creation of new knowledge.

I come from a fairly extensive background of physics, computer science and collaborations with artists. Initially fascinated with pinball machines

but determined to participate in the digital revolution unfolding during his youth, I taught myself programming. This experience formed the early basis for "playful" experimentation with science through fractals and simulations. The interest led to a university education in physics and to a master's degree in science addressing new features in space plasmas (Schiffler 1997): a subject that is still under investigation by physicists to this day. I have also spent several years collaborating with various media artists on installations exploring physical and simulated environments in Virtual Reality (VR) and media art. After leaving the art world to join the Dotcom boom, he became a professional software programmer, but kept strong connections to both the sciences and the arts. As an avid computer gamer during all these years, his critique of this entertainment genre comes from the users perspective. Therefore, ludic or artistic methods and scientific principles have not been mutually exclusive for him.

In order to explore the transdisciplinary nature of this field of study, the research includes theoretical and practical methodologies to gather valid evidence. Drawing from his experience and background, I have conducted an extensive literature review and an analysis from seminal surveys to define core principles in order to create new game physics element descriptions. These were then implemented in research prototypes and tested in field studies with practitioners (artists, scientists and game developers). The results are documented and analyzed for their effectiveness.

This dissertation thereby proves that by considering different perspectives in game physics, significant value for a broad range of practitioners in distinctly different fields can be achieved.

List of Figures

2.1 Schell's Game Design Elements 12
2.2 *LittleBigPlanet* Screenshot 31
2.3 Venn Diagram of Physics with Game Physics 38
2.4 Age Groups in Survey of Players 62
2.5 Gender and Bias from Player Survey 63
2.6 Preferred Game Genres from Player Survey. 64
2.7 Game Physics Beliefs in Survey of Players 66
2.8 Experience Preference in Survey of Players 67
2.9 Acceptable Real-Physics Ideas in Survey of Players 68

3.1 Lindley's 2D Game Classification Plane 87
3.2 Games Released per Year 105
3.3 Top 20 Game Platforms Over Time 107
3.4 Top 20 Game Platforms/Categories 108
3.5 Game Physics Index of Top 20 Categories 109
3.6 Game Physics Index per Year 110
3.7 Game Physics Index Trends 111
3.8 Platforms and Game Physics Index 112
3.9 Non-Console Platform Trends 114
3.10 Console Platform Trends 115
3.11 Handheld Platform Trends 116

4.1 Caillois' Theory of Games 128

4.2 Juul's Game Model . . . 138
4.3 The Evolution of the 2-D Shooter . . . 148
4.4 Galloway's Moments . . . 159

5.1 Shawn Brixey – Eon . . . 180
5.2 Internet Art Facade . . . 182
5.3 Invisible Shape of Things Past . . . 184
5.4 Algorithmic Echolocation . . . 185
5.5 Non-constant Constant α . . . 192
5.6 *IO_Dencies* Force-Fields . . . 196
5.7 Time Dilation Scenario . . . 203
5.8 Fractal from Hubbard's Pendulum . . . 205
5.9 Particle Shower Traces . . . 212
5.10 Gumowski-Mira Avatars . . . 216
5.11 Physical Fractal Avatars . . . 217
5.12 Pac-Man Potentials . . . 220
5.13 Bit Extraction Timing Sequence . . . 227
5.14 Game Process Entropy Collector Principle . . . 228
5.15 GRACE Gravity Anomaly . . . 232

6.1 *Pendulum Game* Screenshots . . . 247
6.2 Friction Models . . . 249
6.3 Mars Normal Gravity . . . 254
6.4 Double Pendulum Systems . . . 257
6.5 Double Pendulum Dynamics . . . 259
6.6 Friction Drive Control . . . 260
6.7 Chroma Key Effect . . . 262
6.8 *Info Link* Block-diagram . . . 265
6.9 *Info Link* Screenshots . . . 266

List of Tables

2.1 Indie Physics Games 33
2.2 Participant Sources of Game Player Survey 61

3.1 Game Hardware Advances 80
3.2 Evolution of Pixel Shaders 82
3.3 Crawford's Game Taxonomy 85
3.4 Computer Game Taxonomy 92
3.5 Game Physics Index 98
3.6 Game Physics Index per Category 100
3.7 Category-to-Index Mapping 103
3.8 Game Database Statistics 104

5.1 PRNG Usage in Open-source Games 224
5.2 Principles and GPEs (1) 235
5.3 Principles and GPEs (2) 236

6.1 PTR Webservice Interface 243
6.2 PTR Source Distribution 245
6.3 Video Documentation: Pendulum Game 270
6.4 Video Documentation: Artists 271
6.5 Video Documentation: Developers 271
6.6 Video Documentation: Scientists 272

Chapter 1

Introduction

A transdisciplinary critique of game physics is needed to advance the state of the art in the field of computer game design. In this thesis I combine contributions from physicists, game developers, game researchers, and artists to define *new game physics* and show that added value can be created by expanding the design choices available for game developers, enabling artists to create more scientifically robust artworks, and encouraging scientists to re-consider computer games as a viable tool for education and research.

Aims

The investigation attempts to clearly delineate the concepts of games, physics and game physics in order to highlight correlations in these seemingly unrelated fields. This background research supports a fairly wide range of objectives and is a novel approach to computer game design. Some of the main questions this study aims to answer are: What are the limitations in current game physics? Can one derive more broadly applicable principles

that reliably extend such traditional game design? What kind of value is created for game developers, artists or physicists through a transdisciplinary game design methodology? The dissertation specifically aims to:

- Clarify the scope of the term game physics, define common types of game physics elements and relate them to some qualities of the science of physics.
- Illustrate the limitations in current game physics and define the term *pseudo game physics*.
- Survey practitioners (game developers, game players and physicists) that have a stake in game physics advancement.
- Document and examine the reasons that computer games are not generally utilized within physics research itself.
- Define a methodology to generate a numerical game physics index that can be assigned to games.
- Perform a quantitative analysis of game physics across several key dimensions[1] to measure the pervasiveness of game physics over time.
- Analyze these statistics to infer how design goals of game developers and external drivers[2] influence the usage of game physics.
- Extend the historical and current game theory discourse to game physics and locate causes for the limited nature of existing game physics.
- Extract theoretical principles from game theory that can be used to guide the design of improved game physics elements.
- Formulate how possibilities for content creators in the applications of such *new game physics* should be evaluated.
- Define a set of game design "principles" from the theoretical analysis of game physics, quantitative analysis of physics in games, and theories of play.

[1] i.e. game platform
[2] i.e. technology

- Extend the set of principles through a review of videogame and science art, and illustrate how game physics could add value to artistic practice.
- Provide exemplary descriptions of new game physics elements across all areas of game design using a language that can be applied across disciplines.
- Describe a generic design methodology for the construction of new game physics elements.
- Create a computer game implementation as research platform for *new game physics* in order to test the proposed design framework.
- Conduct a field study with the three primary target groups of this dissertation (game developers, artists, physicists) and analyze their perception of the new game designs.
- Qualitatively assess the differences between the three target groups and reflect on any limitations present in the game prototype or game physics element designs.
- Describe the differences between scientists' and artists' approaches when exposed to such *new game physics*.

Methodology

A combination of methods is well suited for such a transdisciplinary study and my approach includes both theoretical and practical means of gathering valid evidence. The theoretical part of the research is non-technical in nature and based upon extensive literature reviews, Internet searches and data mining, online interviews, and online surveys. The applied part of the research is highly technical, combining database systems, documented source code, executable software, websites and unconventional electronic devices to produce illustrative prototypes. The methodologies that this study employed to carry out the above research included:

- A systematic contemporary definition and history of game physics and related concepts such as qualities of the physical sciences was defined.
- A heuristic categorization of computer games, which encompasses a numerical game physics index, was conducted.
- A quantitative analysis on game physics use across different dimensions, such as time or game platform, was performed.
- A critical comparison of theories of play was constructed that shows how theoretical concepts are related to game physics.
- Various seminal surveys with game developers, game players and physicists were conducted and analyzed.
- Science and computer game artworks were reviewed to extract design principles and illustrate artistic uses of game physics.
- Several new game physics elements were developed in detail to be able to transfer the research results into practical approaches.
- Game prototypes were implemented which incorporated the proposed elements.
- A field study was performed to critically assess the value of elements for the various target groups.

Chapter Overview

The research resulted in a body of evidence that has been organized into five subsequent chapters.

Chapter 2 summarizes the contemporary definition of *game physics* and covers connections of game physics to both the science of physics and to game practitioners who either produce or consume game physics. Key concepts in *physics* (such as the scientific method) are presented in order to identify limitations in the game physics of today's computer games and also

to constructively reflect on ways to improve both game physics as well as physics research in the future. The chapter describes the standard forms of game physics that are in use today. It attempts to show that game physics is a common game design element and that there are different types of game physics that can be distinguished. This section also gives an overview of the challenges associated with current game physics implementations and outlines future trends that are emerging. The analysis of game physics elements in nine games (see Appendix C) has motivated me to define *pseudo game physics*. The game examples are used to demonstrate the fact that the concepts of physics within computer games are generally present in simplified versions and use only narrow subsets of physics fields. The final part of the chapter summarizes perspectives on game physics by some of the primary practitioners that interact with game physics. These perspectives have been gathered through interviews and surveys of game developers who make the software as well as game players who interact with it. Game industry outsiders who *may* also have a stake in game physics, like physicists, were also interviewed.

In chapter 3, a statistical evaluation of computer game physics has been conducted by defining and aggregating a numerical measure of game physics. This evaluation deepens the previous analysis by identifying trends in certain aspects of game physics such as pervasiveness, dependency on technology, and implicit design goals. The first part will provide a categorization of computer games to analyze game physics across the various genre segments. This overview is followed by the definition of a *game physics index* that describes game physics numerically. By applying this index to a database of game titles, index averages per genre and hardware platforms over time have been generated. A wide variety of graphs are used to discuss and reflect upon the questions raised by this chapter.

Chapter 4 provides a theoretical analysis of game physics through a lit-

erature review of texts about the *theories of play*. This review forms the basis to identify mechanisms by which physics could enter computer games in a meaningful way. It combines historical texts from Huizinga and Callois, with more recent theories by Koster, Juul, Galloway and others. Throughout these reviews, an attempt is made to extract key points that are deemed relevant to this study and that inform the efforts in this dissertation to advance game physics

Following these foundational investigations, chapter 5 combines the insights obtained in the preceding chapters into a set of design principles in order to propose "new game physics." These novel game design elements are derived from the basic element types of game mechanics, game story, game aesthetics and game technology by taking physics into account. Artistic approaches to games and physics are also analyzed, so as to capture non-technical views, alternative metaphors, and unconventional methods. Some of these perspectives can only be found in videogame or science art and additional principles can be extracted from such art practice. Exemplary *game physics elements* (GPEs) in all aforementioned element types were developed by applying the stated principles. With each described GPE, I have created conceptual building blocks, which can be used in a broad range of applications, from computer games to interactive art installations. The chapter concludes by summarizing all examples and deriving a general GPE design framework for practitioners.

Chapter 6 describes the prototypical implementation of *new game physics* in actual games that combine several of the proposed GPEs. These implementations include the *playtrulyrandom.com* Web service as well as the *Pendulum Game*. Subsequently, I present and analyzes the results of a field study performed with these research prototypes. Three specific audiences were targeted for this research, the game developers, the artists and the scientists. During this field study, the players' interactions with the *Pendulum*

Game were documented using video recordings that are summarized online and on a DVD that accompanies this dissertation. A critical analysis and comparison of these interactions has been performed in order to identify those GPEs which have the most impact on the game, to suggest improvements to elements that did not work for the audiences, to evaluate the potential of creating knowledge transfer from such game physics, and also to assess how *new game physics* may affect the different targeted user groups.

Summary

This investigation demonstrates, that more research on game physics is needed. The guiding principles presented in this study can be used to advance the field of game physics design by adding value for content developers and users from different fields. The primary novel aspect of this dissertation is the transdisciplinary approach to game design. It yields valuable contributions about the topic of game physics to a range of research fields by providing seminal surveys, unique analysis methodologies, a new design framework, and an extended game prototype with associated field study documentation. I believe that it will not be easy to bring cross-disciplinary teams together; because members from the game development, art and science communities do not share the same vocabulary, they differ with respect to their familiarity of the complex physics formalisms, and they tend to solve problems using significantly divergent approaches. The results of this research will show, however, that new games physics elements add value for all three groups of content developers. Can we expect better games in the future? I definitely believe this to be the case, once a well-informed and transdisciplinary approach to game design is used. Some results of this theses have already been published (Schiffler 2010) and other game researchers may reuse the source code written for this dissertation which has been made publicly available on the Internet (Schiffler 2011). I continue to actively research some of the

questions raised in this thesis, which should yield further publications about *new game physics* in the future. I also plan to conduct several game design workshops on practical aspects of *new game physics* specifically targeting game developers to raise awareness of the creative opportunities this thesis has uncovered and attempt to practically exercise transdiciplinary game design. Furthermore, I am in the process of designing and implementing a game for mobile devices by applying my game physics design framework and make some of the game physics elements described in this thesis available to a broad audience of game consumers.

Chapter 2

Game Physics

2.1 Introduction

In the title of this dissertation, the word *physics* is combined with the word *game*, implying that such an unlikely relationship exists and should be investigated. "Game physics" is indeed a valid combination and commonly refers to the introduction of the laws of physics into computer-based animations, simulations and games (Rhodes 2005). The goal for this chapter is to provide a concise definition of the term, highlight issues with current game physics, introduce the additional term *pseudo game physics*[1], and give a cultural context for game physics production and use. The contemporary definition of game physics given in this chapter is of paramount importance for the understanding of how game physics can be located within the context of computer-based media, and how it might be critically analyzed and constructively rethought. The chapter concludes by providing perspectives

[1]The term *pseudo game physics* applies when concepts of physics are used in a simplified or otherwise limited form in computer games.

on game physics of the primary practitioners that interact with this design element, including game developers, game players and scientists. This chapter thereby forms one of the foundational pieces, which, when combined with game theory principles that are described in chapter 4, enable this study to constructively reflect on game physics advancements.

2.2 Physics and Context for Research

Since the scientific term *physics* is used rather uncharacteristically within the realm of game theory, a brief disambiguation and scoping is included in Appendix B of this dissertation. A Venn organization of physics into overlapping central theories will be used later in this chapter to determine the breadth of physics coverage in computer games. Four characteristics can be identified as playing an important role across fields of physics: the rigorous application of the scientific method, the belief in an underlying unity of nature, the reliance on the language of mathematics, and the quest to increase the precision of experimental results. In particular the ubiquitous use of mathematical abstractions and formalizations is very closely connected to modeling and simulation as the core methodology in current physics, which in turn is the basis for all physics found in computer games. I relate these important characteristics of physics to the premise of this research, which claims that it is possible to combine physics and games in a meaningful way. Identifiable key issues for physics are the outsiders' widespread perception of physics research being just an intellectual exercise, the challenges surrounding the classical vs. modern physics dichotomy, and an ongoing internal debate on how to make progress in the future. I conclude from this analysis, that physics is often confronted with criticism, both from insiders and outsiders of the field, and posit that these issues can constitute either an obstacle or an opportunity for game designers who may consider physics as a resource.

2.3 Standard Game Physics

Game designs do indeed often include physics, and this section therefore continues to describe this specific computer game feature in more detail. In a computer game, the machine participates in many roles: as referee or opponent, representing a playing field or game tokens using animated graphics, simulating the element of chance or the properties of a game-world, immersing the player in a virtual arena or generating sounds when buttons on input devices are pressed. Of all these roles, this research focuses on the area in which numerical physics calculations are used to enrich games with some form of physics-based realism. This section will explore the most common past and existing uses of physics by game designers to define *standard game physics*, and it will reflect briefly on the current trends in this area of technology, in order to define the current state of the art in game physics.

2.3.1 Game Physics as Design Element

By developing descriptions of design elements in digital games that pay particular attention to the role of game physics, I will show how standard game physics fits into the design process for computer games.

Schell (2008, pp. 41-43) posits that computer game design builds on one of the four essential "basic elements" of game design: *mechanics* (i.e., the gameplay), *story* (i.e., the narrative), *aesthetics* (i.e., the look) and *technology* (i.e., the device). As illustrated in figure 2.1, each basic element (shown as circles) must be interconnected with all others during the design process. Furthermore each element is more or less visible to the player while playing the game. Research into the structure of the mind suggests that the two different sides of the brain control two different "modes" of thinking. Left-brain thinking is dominated by logical, rational, analytic and objective thinking,

whereas right-brain thinking is more random, intuitive, holistic and subjective. The basic elements exhibit therefore a hemispheric brain preference, and good games balance elements across both sides to provide a rich play experience. Any practical game designs are highly specific: for example, an element might be the actual shape of the game avatar or the sound that plays when the player scores a point, but game element implementations can always be placed into one of these basic element categories. Therefore, I have concluded that all basic element types include game physics elements, as illustrated in figure 2.1 by tabs.

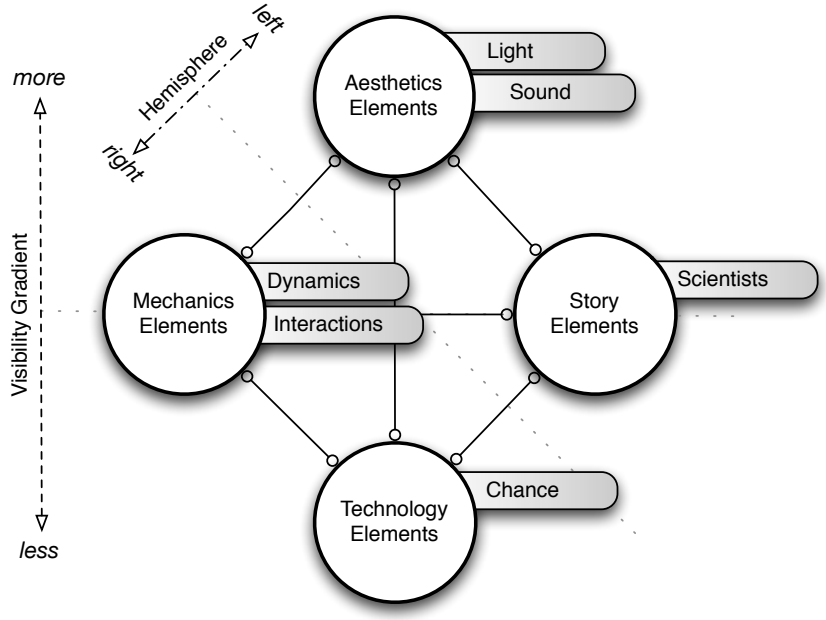


Figure 2.1: The four basic game design elements (circles) with associated game physics elements (tabs); adapted from Schell (2008, p. 42)

In order to identify game design elements, another valid approach is to look at the process of game production and the various roles people take on during the design process. The aim of computer game design is ultimately to

combine the artistic and technical process in order to convert a game idea or concept into an actual application that can be used by players. During game creation, either a single developer or, more commonly, a multi-person development team will define and produce content in several design categories. Wikipedia (2010*a*), for example, lists the categories of graphics, 3D modeling, sound, music, gameplay rules, story writing, level scripting, user interface, network communications, artificial intelligence *and* game physics, as necessary aspects of most game productions. This categorization is reflected in job offerings for game development, and professional specializations for game physics do exist. The site *Gamasutra*, for example, regularly lists positions for the sole purpose of designing the "physics engines" of games.[2] Thus, at least as far as the game industry is concerned, game physics is currently treated as an "equal" element when compared to more traditional ones such as designing graphics or composing music.

Based on the previous examples, the implication here is that game physics is a recognized game design element. Furthermore, it can also be shown that it is a relatively important one. Computer games attempt to focus the attention of the player onto the game space, and the implementation of a physically accurate representation of this space aids in this task. Therefore, the emulation of real-world behavior through physics simulations is treated as a key part in many game designs. The importance of physics as a design element is not merely a design choice, but actually has a root cause: the implementation of physics in a game provides the player with a known framework and point of reference in an otherwise abstract game world. The game designer who constructs a VR game makes it playable by assigning recognizable behaviors to individual game objects. The most well known behaviors of objects for the player are the *physical* ones. For example, game objects on the screen often follow the laws of gravity (by falling down) to look "realistic" and thus

[2]See `http://www.gamasutra.com`

become immediately recognizable and usable, even by an untrained player.

One can observe that advances in game technology have caused game physics to become a mandatory element in game designs. Since 1990, the availability of affordable acceleration processors for three-dimensional (3D) graphics in video cards has caused a proliferation and domination of the game genres that utilize a 3D representation of the game world. The game space is typically viewable from a first- or third-person perspective of the game avatar. Since it is necessary to implement a quite sophisticated kinematics of body movement in a 3D space to make the first-person camera control or the third-person avatar motion usable for the player, any game designs using these perspectives require the use of physics models. This component of game technology is generally not perceived by the game players as a distinct game element, because the whole game world as well as the players' view of it is "holistically" controlled by the physics simulation. Nevertheless, such *physics engines* are present in all games using 3D perspectives and game physics constitutes a prerequisite to make most 3D games actually playable for users.

In conclusion, game physics is a distinct game design element derived from any one of the fundamental element types: mechanics, story, aesthetics or technology (see figure 2.1). The implementation of game physics has become a specialized profession within the game development community. Widespread forms of visual game perspectives critically depend on the implementations of physical simulations.

2.3.2 Types of Game Physics

When defining the term *game physics* in more detail, many deeper questions arise, such as: What genres of games apply game physics and which field

of physics is actually used? How do we decide if an algorithm or game element is considered to be physics-based? The approach in this section will be to answer these questions in order to demarcate the existing standard game physics from the proposed new game physics, because without this demarcation, it will be hard to evaluate the potentials which are not being valued.

The term *game physics* is meant to apply to computer games or computer-based media, rather than games in general. In the domain of screen-based digital games, often called *video games* or simply *computer games*, the integration of physics into a game is primarily focused on the programmatic implementation that contributes to the creation of the audio-visual content and the accompanying interactivity that make up the game, but does not include the design of physical interfaces.[3] To determine which areas of physics ("the science") are used in game physics ("the application"), a categorization of the various types of game physics is required. I have distinguished the following game elements that require the integration of physics into games:

- Physics of the virtual space (i.e., light and sound)
- The physical interactions of objects within the virtual space (i.e., gravity and collisions)
- Characters and narratives involving physics (i.e., names of physicists or physics terminology)

Simulation of Virtual Space

Many computer games already create a virtual representation of space through graphics and audio algorithms, which are based on the simulation of physical

[3]While physical interfaces such as force-feedback input or other haptic devices are used in computer games, they concern themselves not primarily with physics, but rather add a new sensory layer or stimuli to the game play and do not add more physics to the game.

properties of space. For example: the perspective of the walls of a dimly lit dungeon hallway, the image of the misty atmosphere on a planet as seen from a spaceship, or the sound of a gunshot fired by an opponent avatar. Although these examples are all game design elements which facilitate the creation of VR for the player, as noted in section 2.3.1, they simply enable gameplay in a simulated 3D environment.

The *physics of light* (optics) is used to create the visual representation of the virtual space. This type of game physics is based on rules that determine how a beam of light reflects, bends and refracts, and changes color and intensity, to control the visual appearance of the game world. The fidelity of the optical simulation determines how realistic things look. Computer games often use approximations for this type of game physics, to create representations of specific surface properties such as rippling ocean waves, refraction, Fresnel reflectance and iridescence. The "look" of a game is so important for game designers (and the marketing of the game), that even in early games, which did not have the computational capabilities of current computers, light simulations already played a very important role in game technology.[4] Much effort was spent on this aspect during game design and programming, apparent in the various "software rendering engines" developed by the industry. Today, the hardware accelerators that generate the visuals for computer games are a major driving force in the graphics chip industry. Competition amongst manufacturers leads to innovation, which yields some of the most complex integrated circuits ever build – all in an effort to simulate the physics of light.[5] But is this opportunity actually used

[4]Some of the earliest examples of games used a light-simulation technique called "ray-casting" to created a pseudo-3D (2.5D) space representation are *Wolfenstein 3D* (id Software, 1992) and *Comanche: Maximum Overkill* (NovaLogic, 1992).

[5]Manufacturers of Graphics Processing Units (GPUs) have been able to take better advantage of Moore's law (Abi-Chahla 2008) and these devices, such as the 3.9 Billion transistor *Fermi* from NVIDIA, were the most complex microchips when released (Glaskowsky 2009).

to generate *realistic* representations of space or are there limitations inherent in these technologies?

The process that games use to generate an image from a model of space is called "rendering." The model is a purely abstract data structure, which contains information on geometry, viewpoint, texture, lighting, and shading. An algorithm assisted by the graphics hardware uses this information to calculate the final digital image representing the scene. Almost all current spatial simulations in games are based on polygonal rendering via the "DirectX" or "OpenGL" Application Programming Interfaces (APIs).[6] Publications about game design generally accept this technology-driven status quo as the prerequisite for any new game. Conger (2004), for example, states in his book on game physics, "These days, games are usually in 3D," and then dedicates an entire chapter on the topic of "simulating 3D with DirectX." While this process of "scan-line rendering" represents a computer simulation of physical phenomena, the polygonal representation of space and objects does not provide support for an accurate representation of many optical properties such as light emission, reflections, shadows or volumetric properties such as smoke. Furthermore, since triangles are used as surface "primitives," curved objects often have visible geometric distortions and edges show aliasing (staircase effect). Although more accurate techniques such as *ray tracing* or *ray casting* exist and are used in film and television, their computational complexity is much higher, so they cannot be used for the real-time environment of games on existing computer hardware. For this reason, the physics of light remains highly approximated in almost all current computer games as of this writ-

[6]In a polygonal representation of space, all visible surfaces are represented as triangles positioned in 3D space based on the eye-position and perspective transformation. Each triangle is associated with specific optical properties such as color and translucency via static or dynamic textures (images or algorithms). The 3D accelerator will then render' a scene by drawing all visible triangles onto the screen in a specific order (reverse Z-order or back-to-front) drawing pixels onto the screen. The final composite image is then shown as the optical approximation of the 3D space it represents.

ing. I claim that due to this limitation, the physics visually observable by the viewer in games has little scientific value, supporting the premise that different approaches to game design are needed, if the goal is to turn games into tools that support science.

A second element of space commonly simulated in computer games is based on the *physics of sound*. Audio playback on digital devices is mostly an engineering problem. The production of dynamic sound characteristics (sound effects) like echoes or the pitch-shifting Doppler effect is an application of the laws of the physics. Today's games employ sophisticated methods to create "audio immersion" through real-time simulations of atmospheric pressure waves within the 3D environments shown on the screen. A trend similar to the use of specific hardware components to simulate light using dedicated GPUs has occurred. Specialized audio processors that possess computational abilities of small super-computers are standard in today's game PCs and consoles, all in an effort to accurately simulate sound.[7] Because of the availability of hardware-assisted sound output devices and the comparatively low computational complexity of the algorithms to simulate the physics of sound, environmental audio is fairly accurately represented in computer games. Nevertheless, incorrect physics is present in many audio designs of computer games. Typical examples of such *pseudo game physics* in audio effects are the noisy space-ship explosions and "wizz" of laser beams in game settings that take place in outer space.[8]

[7] The *X-Fi* technology by Creative Technology Ltd. (2010) is a good example of such hardware. The audio processor *E-MU 20K1* contains 51 Million transistors operating at 400 MHz and its computational power is estimated at 10,000 Million instructions per second (MIPS).

[8] These game elements should be silent, because a vacuum provides no medium for sound propagation, but they are often the main audio background for many genres of computer games.

Simulation of Virtual Objects

Once the virtual space has been created using the game physics described earlier in this section, game players are usually enabled to interact with other game elements such as avatars and objects. Examples of objects that interest game developers and need to be simulated in a game using physics include: a bridge, a rope, a robot arm, a vehicle, a tower of boxes, or a human.

The algorithms used to simulate Newtonian physics within the virtual environment are referred to as *object dynamics* of the game, and these are generally considered the *only* type of game physics in the reference publications on the topic by Bourg (2001), Eberly (2003), Palmer (2005), Millington (2007) and others. This practical but narrow view reflects one of the problems noted earlier in section 2.2, which is the difficulty for non-physicists to recognize the fact that Newtonian mechanics is not the only important theory relevant to macroscopic systems.

The following simulation elements are cited as belonging to the physics of object dynamics, and they define the status quo of game physics:

- *Rigid Body Dynamics* or *Kinematics* is an area that attempts to simulate the steady state and collision response of simulated objects. It is a very common game physics element, which applies Newton's law to virtual objects. This application leads to the calculation of forces, momenta, and inertia, and it uses a large variety of mathematical methods and abstractions. Solid objects and joints with friction and spring-like behavior are simulated, resulting in motions from simple bounces to complex skeletal animations.

- *Gravity* is an even more common game physics element than kinematics. Game rules that simulate falling objects or jumping game charac-

ters are examples of game physics that can be categorized under the label "gravity." The use of gravity is so common in games, that it is generally not even considered a game physics element, even though it is a form of game mechanics which relies on the application of physical laws.

- *Collision Detection* deals with the simulation of mathematical representations of physical game elements such as boxes and balls. Typical implementations deal with the fast and accurate detection of collisions between circles or spheres, for example the simulation of elastic collision responses commonly applied to ball-like objects (i.e., "pool-hall physics"); and character interactions also require collision detection algorithms.

- A specialized combination and subset of rigid body dynamics is called *Vehicle Physics*. Linked to a long tradition of programming racecar simulations, vehicle physics is a well-researched and documented field. It attempts to describe motion of cars, aircraft, ships, hovercraft and other vehicle types through the virtual space using physics simulations that solve specific hydraulics problems and describe suspensions or tires using physical models.

- Another very common subset of object dynamics is *Projectile Physics*. Similar to the popularity of vehicle or flight simulations, projectiles and gunshots have been used in a large percentage of games since the 1970s. Thus the determination of "the path of a cannonball" was one of the first applications of physics in early video game programs such as *Artillery*.[9] This type of game physics remains in common use in current

[9]The game *Artillery* was written by M. Forman and published in the *Creative Computing* magazine in 1976 as BASIC source code (Forman et al. 1979).

casual games such as the popular *Angry Birds*[10] (Rovio Mobile, 2009).

For some game genres, object dynamics plays a central role. For example in golf, flight or driving simulators as well as many sports games, the main theme of the game *is* the emulation of real, physical behavior of the game objects on the screen. Game designers producing games in this genre are differentiated from each other by comparing the quality of their physics engines; and significant development efforts are spend on the software that is used to animate the simulated objects in a realistic way. Millington (2007), for example, includes an extensive list of "Useful Friction Coefficients for Games" in the appendix of his game physics book, specifically for the purpose of implementing accurate vehicle simulations. In the context of this research, some examples of computer games represent good precedents, since their accurate implementations of game physics are known to elevate the quality of the game.

Characters and Narratives

Depending on the definition one adopts to describe a *game narrative*, game physics elements can also be identified by re-examining the stories of computer games. As Miller (1990) once suggested, if one treats narratives and stories in computer games as ontological and oriented towards creating fictitious worlds, they would form a type of postmodernist literature. Juul (2001) also points out: "The player clearly tries to discover how the game is structured – which is epistemological. But creating a game is clearly creating a world, and one that is usually without special reference to anything." Based on such a definition of narratives, I consider *narrative game physics*

[10] *Angry Birds* is a puzzle game for mobile devices in which a player uses a slingshot to launch birds at pigs and has sold millions of copies since launch (The Week 2011). The popularity has also been attributed to a human evolutionary preference for parabolic ballistic trajectories. (Ridley 2011)

elements. The roles played out within these narratives are an essential part of the whole, because of the cognitive associations they create for the user. This section therefore attempts to illustrate common ways where physics can be located inside the "interactive fiction" of games.

Two distinct forms of narratives in games have been described by Salen & Zimmerman (2004) as "embedded" and "emergent." The embedded narratives are the "pre-generated content that exists prior to a player's interaction with the game" and "tend to resemble the kinds of narrative experiences that linear media provide." Emergent narratives "arise during play from the complex system of the game" as the game rules are coupled with player interactions in a context-dependent way. Both types of narrative game elements contain characters, events, and patterns. In agreement, I have found several game elements that fit these narrative types and are derived at least partially from physics:

- *Science fiction games* make use of the science fiction genre and generally apply physics in a variety of ways. Games in this genre may involve technologies that contradict known laws of nature, or involve applications of new scientific principles.[11] In this form, the physics is instrumentalized to generate a "suspension of disbelief" provided by the potential scientific explanation to various fictional game elements. Often, science fiction games are a secondary commercialization derived from existing science-fiction movies or books and thus mirror or extend their narratives.[12]

- The *mad scientist* character, while not strictly a physicist, is a very common game design element. Wikipedia (2010*b*) references over 50 ex-

[11] Example of such science fiction themes include time travel, nanotechnology, faster-than-light travel, or alien environments.

[12] Game publisher *LucasArts* has for example published over 60 games to date, including online versions, based on the *Star Wars* (Lucas, 1977) movie series.

amples under the "mad scientist" heading, and Whiskey Media (2010) lists over 90 games where such characters play a key role. The character representation is typically stereotyped as male, with the title "Doctor" (80%) or "Professor" (10%), a German name or accent, and a resemblance to Albert Einstein (10%), and an attire that includes glasses, a lab coat or robotic body parts. The narrative often follows Shelley's *Frankenstein* plot to setup the game conflict or have the scientist become the antagonist of the game. Alternatively, the physicist is relegated to an instrumental and expendable secondary character for achieving certain game goals.[13] Such narratives reinforce the positioning of the character as an "elitist scientist" and tend to relegate the player as "the outsider."

- Physicists may also appear as *historical characters*, mostly in quiz, educational or serious games.

- Game scenes, settings and aesthetics may be derived from fictional or actual *laboratory environments*. Indoor representations may provide scene backgrounds for the aforementioned scientist characters; or the game may represent obstacles filled with dangers that the player must overcome.[14] Outdoor structures are often functional game elements representing, for example, "research facilities" which use resources and generate innovations that benefit the player.[15]

- The entire computer game may be designed to resemble a *physics experiment*. Common forms are games where the narrative of "perform-

[13] A community wiki on the game *Half-Life 2* (see section **??**) explains the use for a scientist as follows: "Although cowardly and clumsy at times, scientists can assist the player with certain tasks like Retinal Scanners or opening doors, but they tend to be physically weak, dying within a few shots." (Wikia 2010)

[14] An example lab environment in a game is the "Aperture Science Laboratories" location of *Half-Life 2* (Valve, 2004).

[15] An example of this kind of research facility units are structures of the same name found in the *Command & Conquer: Red Alert* (Westwood Studios, 2000) series of games.

ing an experiment" provides the central game mechanics. Gameplay involves building Rube Goldberg-type devices that are then "run" to solve a puzzle.[16] This type of simulated experiment can often be found in educational games.

Summary of Types

Three types of game physics design elements have been described in this section: *object dynamics simulations* (which is considered the only type of "game physics" in the technical literature), *virtual space simulations* provided by graphics or sound hardware, and *physics content* introduced by science narratives or characters found in many game genres. These design elements comprise the "standard game physics" which need to be further developed and criticized.

2.3.3 Numerical Models and Simplifications

One way to expand the notion of standard game physics might be to closely examine the application of numerical mathematics. Since game physics relies on the digital computer, which uses numbers with a finite resolution as well as operating under memory and time constraints, special algorithms must be used to simulate physics. Non-narrative game physics generally estimates the numerical result of equations based on physical laws. Thus, the implementation of game physics algorithms is typically a problem of numerical mathematics. Examples of mathematical methods used in game physics include the discreet solution of differential equations, numerical integration, quaternion calculations, extrapolation or linear algebra (Eberly 2003, ch. 8-

[16] Examples of games where physics experiment narratives are core to the game mechanics are *The Incredible Machine* (K. Ryan, 1993), *Crazy Machines* (FAKT Software GmbH, 2005) or *Crayon Physics* (P. Purho, 2008) games and their follow-up versions.

10, appen. A). Mathematics may also serve as a tool during game design to analyze when real physics is not necessary and approximations of physics laws might suffice.

Anyone who implements algorithmic game physics has to follow a five-step implementation process which *always* requires the use of numerical methods in step 3.

1. **Process:** A physical process is chosen as a game element. This could be a mechanical or communication system, or even the weather.
2. **Model:** The system is modeled with equations. In game physics, these equations are based on the laws of physics.
3. **Algorithm:** A method to solve the equations is devised. For example, a developer may define a method to describe how a system changes over time.
4. **Program:** A program is written to implement the algorithm.
5. **Simulation:** The program is run.

Can mathematics impose any limitation on this process when used by the game designer? All applications using object dynamics must ensure numerical stability, and physical accuracy is often bypassed in favor of simpler, but more stable algorithms. A simplification of physics in the game is often a necessary step, to ensure that the simulation can be processed fast enough and allow a user to control it in real time. During the development process, a designer may find that the algorithm's implementation may need to be adjusted, so that it can be updated with sufficiently high frequency. Early computer games that ran on computers with very limited computational power represent good examples of the usage of highly simplified algorithms

that led to crude and non-physical simulations.[17] Game physics is also not immune to the issue of under-specification when probabilistic algorithms are employed in game mechanics, causing bias in random numbers or chance calculations (Compagner et al. 1997). In all cases, the approximations are a direct result of the discreteness in the digital representations of values.[18] It should be noted, however, that the degree of error in a numerical simulation depends largely on the choice of algorithm made during the implementation process. The game simulation's failure to reflect real physical behavior may result from the decision to maximize the participant's real-time responses to interactions or the implementation may simply attempt to meet some expectation of the players for cartoon, drama, exaggeration and playful challenge.

2.3.4 Trends in Game Physics

This section will describe and summarize some of the important trends in game physics in an effort to evaluate how they influence game design. In particular, it will be shown that object dynamics is the most common type of physics-based design element used in games because it benefits most from advances in software and hardware technology.

Physics Engines

Game space and game objects are most often represented as polygons, because this is the standard way through which current game hardware can represent virtual space on the display. Since the dynamics of objects is gov-

[17] An example of such limitations affecting early computer games can be observed in *Space Invaders* (Taito Corp., 1979), where enemy bombs drop in a non-physical linear motion.

[18] A accuracy of a numeric representation in a computer is limited by the number bits used to store the number. For example the binary format for a *double precision* floating point number occupies 64 bits and its significand (mantissa) has a precision of 53 bits, or about 16 decimal digits.

erned by a fairly limited set of equations derived from Newton's law that are re-applied to common object abstractions, the software industry has created "middleware" for game development.[19] These software libraries are also called *game engines* and may include functions for graphics, sound, or Artificial Intelligence (AI). Almost always, a subset of the engine's functionality is specifically designed to approximate the evolution of physical systems over time. Such a specialized middleware for physics is called a *physics engine*. Rather than serve as scientific simulations, these middleware programs are designed to run fast and be easy to use. These features usually come at the expense of accuracy, as was described in section 2.3.3. Some examples of commercial game physics middleware are *Havok Physics* (Havok, 2000) or *PhysX* (Nvidia Corp., 2004). Another example is the simpler two-dimensional (2D) open source engine *Box2D* (Catto 2007) that has been widely used in the development of games of the "physics-puzzle" genre. Some newer engines such as the *DMM Engine* by Pixelux Entertainment (2010) extend rigid body dynamics by using finite element analysis to create simulations of soft body dynamics which would "allow players to shatter walls, bend steel beams, turn trees into jelly and many other previously impossible feats."[20]

As a result of middleware availability, commercial game designers tend to spend less time on the development of their own dynamics simulations, and game physics has become more readily accessible to the non-professional game developer. Still, some game companies decide to create their own custom engines to gain a competitive advantage or to cover simulation scenarios that are not available in the generic middleware engines. Such physics engines are therefore almost always "closed source" and generally highly protected by intellectual property rights.

[19] Generally such *middleware* can be used across many games and game platforms and lowers the cost of game development for producers.

[20] So far this engine has not been applied in many game titles, but Roper (2010) suggests it should be used to introduce innovative physics-based gameplay mechanics such as a "magic-based game where you could change material properties of objects to solve puzzles."

Physics Accelerators

As discussed earlier, developers who attempt to simulate space make use of specialized graphics and audio hardware in the computer. These are specifically designed computing devices that improve the speed of a narrow set of algorithms used to simulate virtual space.[21] Recently, a similar set of devices became available for physics simulations as well. In 2000, research by Bishop et al. (2000) had provided the basis for a commercialization of game physics acceleration, and by 2005 standard PCs could be upgraded with hardware that speeds up common game physics algorithms (Shrout 2005).

Physics accelerators are specialized computer boards that perform certain game physics simulations – in particular related to object dynamics – much faster than multi-purpose Central Processing Units (CPUs). This hardware advance enables new gameplay options and visual effects, in an effort to further enhance the user experience of 3D games. The first generation of consumer-oriented physics accelerators developed by AGEIA (2007) was capable of enhancing the following classes of simulations:

- Rigid body object systems (collisions, joints, rag-dolls, friction)
- Articulated vehicle dynamics (wheel shapes, joint-based suspensions)
- Smoothed particle hydrodynamics (volumetric fluids)
- Cloth (flags, clothing)
- Volumetric deformable objects (plants or multiple layers of cloth)
- Volumetric force fields acting on objects (gusts of wind, dust devils, vacuum cleaners or anti-gravity zones)

Shortly after the release of these devices, a technical solution was devised

[21] Because these devices have the sole focus on speeding up certain tasks and algorithms, they are often called "accelerators."

to perform similar calculations on the latest generation of graphics processors.[22] In order to make the hardware-based physics acceleration accessible to the game designer, it is generally highly integrated with a physics engine middleware. Microchip manufacturers have also latched on to this trend and now market their multi-core CPUs "to assist in better simulations in games," claiming that their processor upgrades enable more realistic game experiences (Cheung 2006). I fears that this development will become a "dead end" for games unless *new game physics* designs are being considered.

Research is also being conducted to overcome the limited accuracy of polygonal graphics rendering by introducing hardware-assisted ray tracing acceleration. Experimental devices such as *SaarCOR* (Schmittler et al. 2002) or *RPU* (Woop et al. 2005) are available today, and the commercialization of ray tracing accelerators initially targeted for film and animation production has begun to filter into the game industry (Caustic Graphics Inc. 2010).

It seems that software evolution tracks predictable hardware advancements: a trend that provides increasingly faster microchips.[23] To date, the main achievement of hardware physics acceleration has been an extension of capabilities that were already available in the software game engines. Therefore, physics accelerators are mostly used to scale existing game physics simulation modes rather than to add new ways of incorporating physics into games. This observation also validates the premise, that only the *combination* of such advances with new concepts and transdisciplinary approaches might actually unlock new creative and aesthetic potentials of computer games.

[22] Due to the high cost of the physics accelerator boards, sales numbers of the devices were low. It was no coincidence that the transition to GPU based physics acceleration occurred in 2008, when a leading supplier of physics accelerator hardware at the time (AGEIA) was acquired by a leading manufacturer of GPUs (NVIDIA).

[23] Moore's law, predicting that a doubling of the speed or density of integrated circuits will occur every 24 months, has continued for more than half a century and is not expected to stop until 2015 or later (Moore 1965).

Domination of Dynamics

As the summary of section 2.3.2 already suggests, dynamics simulations are a dominant form of game physics in computer games. Mainstream game design makes extensive use of physics engine middleware, which not only provides easy access to highly sophisticated object dynamics simulations for the game programmer, but also creates a de facto standard of what is considered game physics today. Advances in hardware technology have also been shown to *scale* rather than *change* the use of such simulations. This section attempts to provide additional evidence of this dominance in mainstream game design and investigates if such a prevalence is preserved in less commercial productions such as "indie" games or in the non-mainstream genre called "serious games."

Some of the latest commercial game developments with a particular focus on game physics, such as Sony's *LittleBigPlanet* (2008) or Crytek's *Crysis2* (2010), do not seem to advance the state of the art of game physics as a game element away from object dynamics. *LittleBigPlanet* (see figure 2.2) for example, simply combines a high-quality 2D object dynamics engine[24] with a well designed 2.5D graphics interface and a community-driven content model.

Such fundamentally limited physics abilities of the software are in stark contrast with the way the game is promoted. The developer advertises the simulation capabilities with statements such as "*LittleBigPlanet* is the manifested embodiment of your perfect dream world" (Sony 2009), and users of the game go as far as to predict that the future of physics education could be based on the compelling nature of the experience. As media strategist

[24] 2D object dynamics engines are game physics simulators found in many games such as *Crazy Machines* (see section **??**) or *Crayon Physics Deluxe* (Kloonigames/P. Purho, 2008). They are relatively straightforward to implement because of their simplified 2 dimensional kinematics which tends to operate on basic shapes such as lines or boxes.

Figure 2.2: Screenshot of the game *LittleBigPlanet* (Sony, 2008)

Howard (2008) writes:

> "I was dreaming of a world where kids fought with their parents in order to spend more time learning physics. Only it's not a dream. It's here today and it is called *LittleBigPlanet*."

Players have also been observed to marvel at the capabilities of the *Crysis2* physics engine, which provides physics-based destruction animations, by posting many videos online showing in-game experiments entitled "3,000 barrel explosions" or "Crysis Nukes! Extreme Graphics Amazing Physics."[25] While players are enthusiastically embracing the experimental freedom these games allow,[26] it should be noted that new game technologies such as the 3rd -generation middleware *CryEngine3* (Crytek 2009) on which the game

[25] Video of *CryEngine3*'s ability to animate a stack of thousands of barrels: `http://www.youtube.com/watch?v=YG5qDeWHNmk`, and of *Crysis2*'s ability to animate the shockwave of nuclear bombs: `http://www.youtube.com/watch?v=e_P0VSZGVko`.

[26] More than 2 million user-created levels have been published for *LittleBigPlanet* within two years of release (Perona 2010).

Crysis2 is based do not introduce any new non-object-dynamics-based game physics.

It is relatively difficult to conduct a general analysis of casual and indie games due to the sheer number of productions and their relative obscurity in the market. Fortunately, the physics game blog *Fun-Motion* (Wegner 2006*a*) does provide a comprehensive list of games that make innovative use of game physics in their gameplay and can be used as a comparative reference. Table 2.1 summarizes this list which contains over 80 games reviewed by Wegner since the blog was launched. The analysis of these games places each title into a category, based on the predominant type of game physics that is used. As can be seen from this investigation, over 90% of the casual and indie games in the list used object dynamics simulations.

Educational and serious games are often produced in small teams by game developers and designers with a background in the casual market, as well as by non-professional game developers such as researchers in various fields. The predominant reason is, that these games are either not very profitable or are publicly funded as part of research projects. As a consequence of limited development resources, serious games tend to leverage existing commercial game engines and thus inherit all their limitations in the process. For example, the *Unity3D* engine was used for the serious game productions *Global Conflicts: Palestine* (Serious Games Interactive, 2007), *WolfQuest* (Minnesota Zoo, 2007) and *Timez Attack* (Big Brainz Inc, 2006), and developers cite the efficiencies gained by such an approach as their main reason for adopting the commercial tool (Unity Technologies 2009). While these games fail to focus on physics training, they exemplify the common use of standard game engines and how this practice automatically provides a default game physics scope to this genre.

Philip Rosendale, creator of the VR game *Second Life* (Linden Labs,

Type	Subtype	Game Titles (Various Authors)
Object Dynamics	Rigid	*Amoeball, And Yet It Moves, Armadillo Run, Barrel Mania, Blast Miner, Bounce Symphony, Break Quest, Bridge Builder, Caramba Deluxe, Coaster Ride, Crayon Physics, Cat Sledding, De Blob, Dodge That Anvil, Double Wires, Factory Pinball, Fantasy Roller Coaster, FlatOut 2, Flyhard, Garry's Mod, Gish, Globulos, Golf?, Gumboy Crazy Adventures, Hammerfall, Hamsterball, I Hate Clowns, Kumoon, Momentum Missile, Mayhem, Motorama, Mu-cade, Obulis, Peggle, Plasma Pong, Pogo, Sticker, Powder Game, Power Shovel, Red, RoboBlitz, Rolling Assault, Ski Stunt Extreme, Ski Stunt Simulator, Solid Balance, Sprinky, Steam Brigade, String Theory, Stunt Hamsters, Squishy the Starfish, Switchball, TG Motocross 2, Tower of Goo, Toybox, Trials, Trials 2,Triptych, TubeTwist, Walaber's Trampoline*
	Soft	*Gish, Soup du Jour, Tower of Goo*
	Ragdoll	*Double Wires, Factory Pinball, FlatOut 2, I Hate Clowns, Lugaru, NekoFight, Rag Doll Kung Fu, Ragdoll Masters, Ragdoll Matrix Reloaded, Rocky the Monkey, Rubber Ninjas, Stair Dismount, Sumotori Dreams, Super Stealball, Teenage Mutant Ninja Puppets, Toribash, Truck Dismount, Walaber's Trampoline*
	Vehicle	*Trackmania Nations, Trials, Trials 2*
	Gravity	*Pluto Strikes Back, Strange Attractors*
	Buoyancy	*And Yet It Moves, Bloboats*
Fluid Dynamics	Flow	*Ichor, The Odyssey: Winds of Athena, Plasma Pong, Powder Game*
	Pressure	*Operation Cleaner 2*
Electromagnetism	Magnetostatics	*Plus or Minus*

Table 2.1: Game physics categorization of indie games in the *Physics Games* list of `http://www.fun-motion.com` (Wegner 2006*b*)

2003), confirms in a keynote speech at the serious game summit that serious game developers accept that game physics is limited to the simulation of Newtonian mechanics. Rosendale notes that "games can be seen as constrained [dynamics] simulations with goals" and describes *Second Life* as "a sort of digital atomic system – small solids glued together to make physical objects." While this describes a sophisticated object dynamics system,[27] his keynote speech places a stronger emphasis on the social aspects available in the VR experience for educational applications; while he ignores, by and large, the experimental scientific capabilities (Carless 2006). Reviews of the game by physicists also mirror this observation, as the proposed uses center on collaborative training, virtual meetings and shared access to scientific data (Medeiros 2008). A similar approach can be found in other game research as well. The GAMMA Research Group at the University of North Carolina at Chapel Hill (UNC) focuses on the development of AI algorithms for multi-agent and crowd simulation alongside secondary traditional game physics topics (Manocha 2009). Yet another example of the dominance of dynamics and preference for the social aspects of learning is the entirely National Science Foundation (NSF)-funded game *Lunar Quest* (RETRO, 2008). The game's homepage[28] describes the project as "Physics education for the 21st Century!" which "combines traditional video game play with the basic principles of kinematics." The implementation uses a Massively Multi-player Online Game (MMOG) design methodology to create a science setting and adds physics specific educational content through "mini-games," the majority of which (80%) are simple object dynamics simulations.

In conclusion, the above analysis demonstrates through examples and reviews of current, casual, indie and serious games that game physics is predominantly understood to be object dynamics by game developers in this market segment. Many new game designs, irrespective of their goals as ei-

[27] Current versions of *Second Life* use the *Havok* game physics engine.
[28] See `http://www.lunar-quest.org`

ther big commercial productions or more serious games for research, tend to use the game physics implementations of existing game engines, which limits the scope of physics to object dynamics. While the increased fidelity and scale of object dynamics simulations are used to create compelling applications of game physics in some newer games, they do not fundamentally advance game physics as a design element. This limitation in game physics has consequences that will be further explored in section 2.4.1 and represents additional evidence that this research into new approaches to game physics is needed.

2.4 Pseudo Game Physics

The application of game physics in computer game design is illustrated extensively in Appendix C of this dissertation. The examples are presented in chronological order and provide an overview of games in several genres.[29] Furthermore, the discussion analyzes each game for incorrect physics or other simplifications. It is one of the goals in this dissertation to question if the physics used in a game is "true" physics, rendering simulations that match the scientifically accepted descriptions of nature.

As the reader can observe from this analysis of game physics, even the earliest games used physics through the notion of gravity acting on objects (*Space Invaders*). These simple simulations were quickly generalized into 2D object dynamics (*Asteroids, Arkanoid, Mario Bros., Crazy Machines*), 2D inertial control (*Asteroids*), simulated friction (*Crazy Machines*), 3D object dynamics (*Battlezone, Battlefield 2142, Half-Life 2*), and physical character and "ragdoll" animation (*Battlefield 2142, Flatout, Half-Life 2*), as well as the narrative use of physics metaphors and narrational characters (*Crazy*

[29] A descriptive taxonomy of computer games is developed in section 3.2.2, proposing a list of game categories used in this research.

Machines, Half-Life 2). In more general terms, game physics has most often been incorporated into games as a programmatic tool to make the presented "game space" more playable. Furthermore, as is apparent from the games that were presented, the quality of most physics simulations does not hold up to scientific tests. This phenomenon, which I label *pseudo game physics*, has arisen for a variety of reasons. The dissertation proceeds to further investigate in more detail how game physics diverges from "true physics," and it thereby attempts to describe such pseudo physics found in computer games. I will also postulate possible ways in which new game design approaches could resolve such divergences.

2.4.1 Limited Field-Coverage

The science of "physics" was described as a broad continuum of fields consisting of several overlapping sub-fields (see Appendix B). Scientists may ask to what degree this entirety of physics is represented in computer games? Physics research generally adopts the holistic view that all fields must be woven together to make a true representation of the science. I posit that a limited coverage of these fields of physics in computer games is a misrepresentation of physics and thus constitutes pseudo game physics.

A survey conducted by the Entertainment Software Association (2005) states that games which are specifically designed to be accurate physics simulations, such as vehicle simulators (i.e., *Flat-Out*) or flight simulators, make up less than 5% of all game titles sold. Based on this broad observation, I suspected that game physics might be quite limited in the scope of its use of physics fields. If, for example, no game exists that embedded nuclear physics in its simulations, this particular field would be considered as *not covered* in game physics design. Based on this methodology, a Venn diagram of fields of physics can be augmented by identifying all fields which are being observed

to be present in games (see section 2.3) and highlighting them as colored areas.

Figure 2.3 uses a background tint to indicate fields covered by standard game physics. Object dynamics, which is widely applied in games, covers the fields of particle-based classical mechanics such as Newton's law of motion, Lagrangian mechanics, Hamiltonian mechanics, kinematics and statics. The simulation of virtual space as described earlier in section 2.3.2 extends the field coverage to waves and fields, while the simulation of sound adds acoustics and more general dynamics. Similarly the 3D representation of space is mostly a simulation of geometric optics, a subtopic in the field of electromagnetism. However, the standard polygonal representation of space is so simplified that it does not require the use of Maxwell's equations, which describe the interactions between electric and magnetic fields as well as electromagnetic flux. Finally, the bases for all game physics are computational simulations of physical laws through numerical models as described in section 2.3.3. This adds partial coverage to the field of computational physics, as some algorithms found in the sciences are obviously applicable and used in game programming. However, it should be noted that although some indie games have experimented with the integration of fluid dynamics and electrostatics in their game design, these are not commonly accepted game physics elements; therefore they were not considered to be part of the coverage in this diagram.

As the modified Venn diagram (see figure 2.3) shows, only a very limited coverage of physics research fields has been achieved through standard game physics. Out of the 12 subfields found in the diagram, only 4 are commonly found in game physics designs; thus a maximum current coverage estimate is 25% of all fields in physics. This is a clear indication that there are significant opportunities to expand game design by using more physics fields. Although the term *physics* is associated strongly with the game design element of game

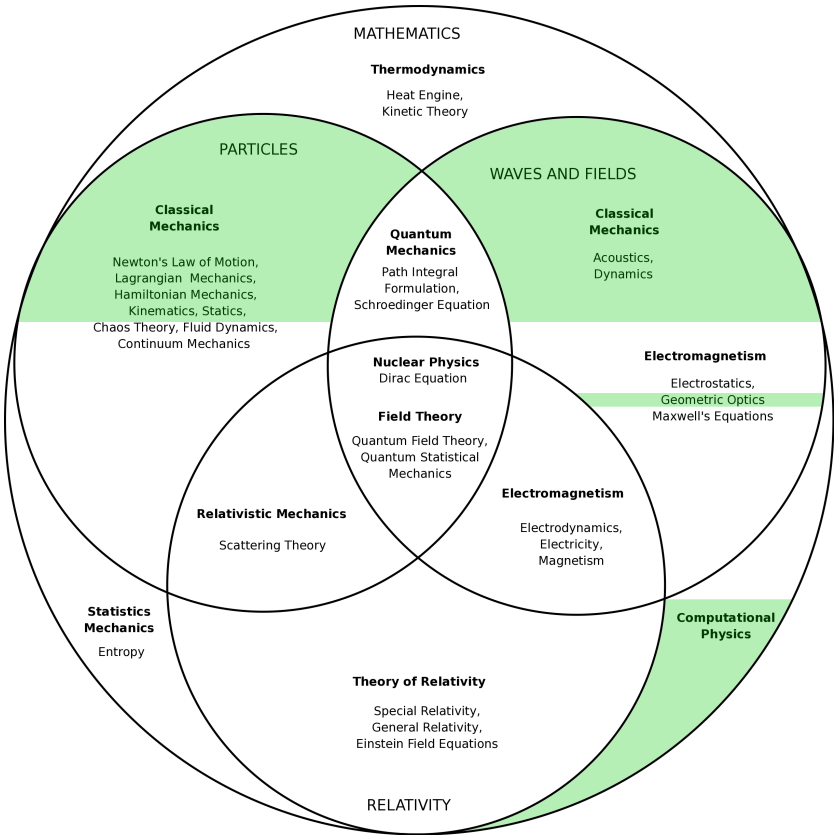


Figure 2.3: Venn diagram of subfields of physics in *standard* game physics: the areas used by game physics in current computer games are colored.

physics, this association obscures the fact that games deal only with dynamics, acoustics and optics rather than the "whole" of physics. Therefore, the term *game physics* already constitutes a form of pseudo physics, as it represent an inaccurate use of terminology and an inherent simplification when applying only principles of classical physics (such as Newtonian mechanics) and disregarding most aspects of modern physics (such as Quantum mechanics). As this finding suggests, game physics could be advanced by devising ways to include previously unused fields of physics into game designs, an area

of exploration which will be addressed in chapter 5. I believe that transdisciplinary teams are best equipped to expand the coverage of fields of physics in games.

2.4.2 Lack of Precision

One of the main characteristics of applied physics is the scientists commitment to precision because the scientific method is being used. Since games predominantly focus on entertainment, precision in game physics simulations is only a secondary consideration and not a priority for the game developers. So why could it be important to embed precise physics in computer games? I posit that a lack of precision has detrimental effects on how scientists appreciate computer games.

As most game examples presented in Appendix C illustrates, the accuracy of a physics-based simulation is generally not considered by designers of games. In physics, precision relates to the characterizations of a problem and requires the definition of uncertainty. Measurements in scientific work are usually accompanied by estimates of their uncertainty. Computer games never expose the limitations of their simulations, mainly because they use *black-box* game engines or implement deliberately non-physical algorithms to achieve a specific game effect. In the sciences, one of the main goals of the scientific method is to limit uncertainty by making more precise measurements, because increasing the precision usually means improving repeatability and reproducibility of the predictions.[30] The design of most computer games does not facilitate measurements of values or allow the player to obtain the actual results of game physics simulations other than through the game action. While many games feature gauges and Heads-Up Displays (HUDs) as overlays, they are almost never used for quantitative measurements; and if

[30] i.e., weather forecasts

they are, they often lack scientific units.

On a practical level, the pace of most games would not even allow the player to take account of a readout of values from such HUDs. By the same token, I have never found a game design that includes the numerical assessments of the game physics simulation by an independent scientific body (peer review), even in games of the simulation genre.

It is unfortunate that game physics has so little focus on the precision of its applications, because precision is the main motivator of research activities. It is even a factor in political decisions that are based on scientific results. This latter point can sometimes lead to an extensive debate about the precision of a theory or a dataset.[31] Without doubt, almost every scientist values the understanding of the precision and accuracy of their theoretical constructs and measurements, particularly when the experimental domain is explored. Thus, in the context of a social discourse involving science, game developers should help the general public to better understand the scientific methodology by seeking precision, or at least striving to be able to evaluate it. Perhaps the precision of the physics is lacking in games because it is considered a "luxury" in the gaming context. It is work for the game designer to implement accurate algorithms, and it may require specialists with scientific training. More precise algorithms could also slow down the pace of the game considerably. Consequently, precision in game physics is largely ignored and as an unfortunate result games cannot be used in a scientific context.

The following two examples illustrate why game physics *should* consider precision as an integral element:

- Children learn during science education that their senses will not al-

[31] A good example of such a politically motivated "precision debate" is the media attention during 2006–2008 surrounding the scientific evidence of global warming.

ways deliver precise information. Although it is possible to estimate distance, the actual length can only be obtained from measurement. Measurement translates *qualitative* information into *quantitative* information. Different kinds of measurements are carried out in science, and this process is fundamental to prove a hypothesis. In fact, a documented gap exists between the theory and the practice of precision in teaching materials for science education: textbooks often have a poor track record because the teaching material itself is imprecise or fails to cover the topic of precision adequately (Hubisz 2003). Computer games rarely offer ways to *measure* quantities unless such measurement serves a very specific game purpose (i.e., an educational design). Thus precision in computer games becomes a key issue when games are to be used in an educational context or even as an extension of actual scientific research.

- For researchers, scientific precision can be a psychological factor, because it may satisfy their need for perfectionism and control. The precision of scientific research is even seen by some scientists as its most important feature and therefore must be taken into account during a discourse involving audiences with both scientific and non-scientific views. Game physics targeted to scientific audiences should always consider seriously how it represents and implements precision.

I posit that computer games in which precision is a key aspect of the player's experience, as well as when they are sufficiently open and configurable, might easily become valuable tools in physics education. For example in construction games, level progression could be simulated by an increasingly more accurate physics applied to their statics, ballistics, collision and material fracturing simulations. Such games could be designed in such a way so they are played either in arcade mode using simplified physics or simulation mode with high precision physics. Through accuracy controls, a game could

be configured as needed to become either an action game or an edutainment simulation. The two modes would differ by the number of natural features that are simulated and in how accurate the individual simulations are. Since software is infinitely configurable, one could use such an implementation as a design advantage for the game. Even its use as a scientific tool would be possible at the highest precision level.

In summary, precision is an inherent quality of many applications of physics but not exposed in many computer game genres. While precision in game physics should not be overemphasized, particularly when it might be more interesting for a game designer to loosen the creative rigidity inherent in applying a physically precise simulation, improving the precision of game physics would constitute a new quality in games. For these games to be useful in an educational context and acceptable to scientists, physical accuracy is essential and simulated values must be accessible for measurement. The precision of the simulation should also be quantifiable by exposing error estimates or documentation. However, to what degree a "tradeoff" between educational and scientific uses (by lowering the precision in favor of educational goals) is acceptable to scientists, will be researched through interviews with physicists, as described in section 2.5.3. A further question arises: can precision still be part of the "hyperreal" fantasies created with computer games?

2.4.3 Physical Hyperreality

As communication researcher Tiffin (2001) describes, a *hyperreality* is created when VR and physical reality interact with one another. In computer games, the game physics would place the game player in a hyperreal physical condition during gameplay, which may trick the consciousness of the user to actually accept the behavior of the virtual world as a natural given. Play-

ers may have a harder time to distinguish reality from fantasy, because the creation of a hyperreality through game physics could constitute a type of pseudo physics.

These convincing physical hyperrealities can have significant influences, as a study published in the *Journal of Experimental Psychology* by Kubitzki (2007) has shown. People who play car racing computer games may be more prone to drive recklessly and get into accidents, according to a study by German researchers. The researchers initially questioned 198 men and women. Those who played computer games frequently were more likely to report engaging in aggressive and risky driving and getting involved in car accidents. Then the researchers had 83 men play either a racing game or another type of game, and found that those who played the racing game reported more thoughts and feelings associated with risk-taking than the others, the origin of which can be attributed to the game:

> Driving actions in these games often include competitive and reckless driving, speeding and crashing into other cars or pedestrians, or performing risky stunts with the vehicle. In short, most actions in racing games imply a very high risk of having an accident or severe crash in a highly realistic virtual road traffic environment.

Such research adds to the evidence that computer games featuring realistic environments can influence the behavior of some players. Several other studies including one by Chapman (2010) clearly indicate that a negative influence on the player is caused by the distorted presentation of reality in some driving simulators. The effect is a direct result of the exaggerated dynamics[32] and entertainment-oriented implementation of the physics simulations

[32]The analysis of the game *FlatOut (Bugbear Entertainment, 2004)* in section **??** of this study provides a good illustrative example.

for the vehicles. In the documented cases involving driving simulations, a direct influence was observed that impacts on real traffic safety. Similar research involved the First-Person Shooter (FPS) genre, in which a super-human avatar controlled by the player kills adversaries, and has been found to increase aggression-related actions outside of the game context among players.

In summary, when computer games use a *simulacra of physics* and implement "the simulation of something which never really existed" (Baudrillard 1996) through their game physics implementations, they often create physical hyperrealities. When such hyperrealities are placed within the context of natural actions, then the player may experience negative psychological effects. In the context of this dissertation, distortions in the game physics are the primary "design tool" that create these hyperrealities. I surmise that game physics, which influences the player through such physical hyperrealities, also constitutes a form of "pseudo physics." Through the creation of false hyperrealities in the realm of physics, computer games may even create a new kind of *folk physics* which is practically useless. When a game presents a hyperreality being used as a reality, it conditions the player to respond accordingly to such "Folk Physics" instead of the real physical behavior; however, this is a whole area of future research beyond the scope of this thesis.

2.4.4 Movie Physics

Many commercial successes of the game industry are rooted in appropriating visuals and actions from filmmakers and the movie industry (Cosgrove-Mather 2004). This approach has a long tradition in game design and tends to introduce a range of physics law violations into computer games. The alignment of game design with film in the entertainment industry causes dis-

tinct types of pseudo physics to emerge.[33] This categorization is generally not due to incorrect simulation algorithms, but rather from the adoption of movie metaphors that are already known and accepted by the consumer and incorporated into game design.

As Tom Rogers, the creator of the popular website *Insultingly Stupid Movie Physics*[34] claims, "mistakes, goofs and flat-out destructions of the basic laws of the universe" are frequently found in Hollywood films (Rogers 2007). He lists the following categories of physics violations that are present in film media, which may be summarized as follows:

- Violations of Newton's law of universal gravitation through the unrealistic depiction of the ease of escape from a planet's gravity: by paying no attention to the direction of gravity, allowing impossible landings and takeoffs for spacecraft, and the incorrect depiction of artificial gravity in space environments.
- Violations of Newton's 1st law of motion when using a Second World War naval battle model in space combat, the incorrect depiction of bomb drops from planes or spacecraft, and starting and stopping rotations of large objects at unrealistic rates.
- Violations of Newton's 2nd law of motion when shooting large amounts of ammo without reloading, scaling a living creature to a larger size than biology permits, performing unrealistic jumps, subjecting characters to huge accelerations without causing injury, and performing rapid turns in space maneuvers with no physiological effects.
- Violations of Newton's 3rd law of motion when shooting firearms with-

[33] Science writer John Bohannon made a similar observation in the biology-focused game *Spore* (Maxis, 2008). "According to the scientists, the problem isn't just that Spore dumbs down the science or gets a few things wrong – it's meant to be a game, after all – but rather, it gets most of biology badly, needlessly, and often bizarrely wrong." Bohannon (2008)

[34] See `http://intuitor.com/moviephysics`

out recoil, encountering falls through glass windows that do not cut, and collisions between massive objects and Earth without any consequences.

- Violations of the 1st law of thermodynamics through depiction of size metamorphosis or perpetual motion without a source of matter or energy.
- Violations of the 2nd law of thermodynamics by disregarding the effects of radiant heat and electromagnetic effects of atomic bomb explosions.
- "Creative Kinematics" and unrealistic visualizations in the depiction of explosions and their effects.

All of these violations in the film medium can also be found in computer games. Furthermore, negative movie metaphors of the scientist or physicist cast in the role of an "alchemist," a crazy world-dominator, or a politically-used genius are often appropriated or fused into computer games as narrative elements of game physics,[35] and this exploitation of caricatures further confuses the role of the scientific method in "proper" physics.

Rogers (2007, p. 8) suggests that pseudo physics negatively affects the audience in the long term and that this "foolishness works its way into our collective knowledge as fact, reinforcing major misconceptions of physics along the way." Such misconceptions of physics would "have to be unlearned before the subject can be mastered." Unfortunately, there is little evidence that such "unlearning" is actually done in schools. Students are rarely asked to analyze the faults of physics in games or movies, though such inquiry could be part of the common curriculum. Rogers (2007, pp. 5–6) then proposes a set of guidelines for "safe" movie physics that should not restrict artistic and design freedom:

[35] See also section 2.3.2

- Well-known physics laws and principles should not be broken unless used in the context of a parody, fantasy, cartoon or comic.[36]
- Physics knowledge may be stretched when all of the following four conditions are met:
  - The area of physics modified is not fully understood.
  - The stretch creates a unique entertainment or artistic opportunity.
  - The explanation of the modification is not portrayed as scientific.
  - The first law of thermodynamics[37] is not contradicted.

Although these guidelines contain exceptions that are so broad as to excuse most violations, they may still be applied to computer games and noncompliance can be used to define "pseudo physics." Because any of the listed violations are clearly identifiable in game design as movie metaphors, the transfer of movie physics into computer games constitutes a problematic trait of game physics. The evidence that has been gathered suggests that movie physics and pseudo game physics are both mass culture phenomena which use physics as an element of entertainment.

2.5 Perspectives on Game Physics

In this section I attempt to investigate how the status quo of standard game physics was established, and seeks to analyze views of the production side, made up of game developers, and the consumption side, represented by game players. Since the exposure to physics within these groups is generally limited, physicists were asked to provide input in relation to their roles as "mentors" or consultants. The results constitute a broad description of perspectives on game physics by practitioners who tend to drive game development.

[36]It should be noted, that Rogers does *not* provide more details on how one would weight artistic freedom versus pseudo-physics beyond the general genre categorizations.

[37]The first law of thermodynamics is the principle of conservation of energy.

Why should game physics research focus on content creators? First, game developers and designers are the primary producers of computer games that contain game physics. Second, this group is in a unique position at the beginning of a large distribution chain for commercial computer games, causing their creative work to be viewed, consumed, and played by potentially hundreds of millions of people. Third, game development leverages the unique property of computer software to be adapted, copied and then "multiplied" with negligible cost. Through this multiplier effect, relatively few game developers ultimately define the game genres and thus determine the outreach of game physics. Therefore an analysis that targets this specific group is necessary.

As has been shown in section 2.4, game physics is often limited in its physics field coverage and precision. Do players perceive such limitations, and are they aware of the pseudo game physics present in computer games at all? Evidence of such perceptions has rarely been collected or analyzed. Also, if game physics can create a form of "Folk Physics" that is broadly accepted by players, then how do we imagine shifting or changing this trend? Although it will be difficult, from a single survey, to establish a simple one-to-one correspondence between the widespread use of pseudo game physics in computer games and specific social or cultural implications for the players, the analysis of game player responses can still be used to inform the definition of a new set of game physics elements. These would be designed to overcome limitations of pseudo game physics in a way that is meaningful and acceptable to game consumers, yet are generic enough to be useful across a variety of other game contexts such as art or science and create value for transdiciplinary teams.

If a lack of domain knowledge is indeed responsible for pseudo physics in games, why would game developers not employ experts to assist in the construction of more realistic and comprehensive game physics? With this

question in mind, the third group being asked to communicate their perspectives on game physics is the physicists. The study will search for evidence that indicates the presence of a boundary separating the camps of science and entertainment. Thus a survey of this group will document and evaluate possible reasons that cause computers games to be rarely based on actual physics research, and that explain why game physics is almost never utilized as a research tool within the natural sciences.

2.5.1 Interviews with Game Developers

I has asked several game developers and writers for game design publications to answer a set of questions about games, and about game physics in particular. These interviews were conducted by email during the period of March to August 2006. After an initial correspondence to ensure participation, a personalized questionnaire was sent out to each respondent. I customized each questionnaire with questions referring to the respondents' specific professional background (40% of total questions). The remainder of the questions (60%) were more generic and referred to general topics in game physics, the benefits of realism, and progress in the game industry. The answers were formatted and are included in their entirety as source material for this work (see Appendix E). What follows are summaries of the interviews with eight game developers and writers, with the purpose of comparing their views on game physics.

Alen Ladavac

Alen Ladavac is the lead programmer at Croteam and part of the development team of the *Serious Sam* franchise, a very popular FPS-style game series. The series was first released in 2001, and he noted the difficulty his team encountered during the development process of a game physics engine:

> Getting there was not trivial. But looking at the currently functional system, it really is astoundingly simple. ... Physics is a full-loop feedback process.

When asked about the quality of the simulation he commented:

> Now fakes, there's numerous. ... In [the] Sam series, the gravity is 30 m/s^2.[38] This is because the character is required to be able to jump 2 meters up.

During the interview he confirmed the limited nature and status quo of game physics:

> Gamers are ordinary people and as such, dynamics, optics and acoustics are the only fields they are interested in.

Ladavac posits that the public believes that physics is useless. Therefore, in his opinion, game physics can be much simpler than reality; he also believes that game physics is an easy element to implement for a software engineer.

Chris Crawford

By comparison, Chris Crawford is a longtime proponent of thoughtful and experimental games; he wrote the influential publication *The Art of Computer Game Design* in 1982. His latest project *Storytron* is an effort to create a truly interactive storytelling experience for players. Possibly due to his past and more recent experiences, his outlook on the future of game design is humbling. He suggests:

[38] Gravity should actually be lower than the standard earth gravity of about 9.81 m/s^2 to jump that high.

> In terms of the nature of the challenges we offer players, we haven't even scratched the surface.

He also points out the problem that serious games would face when using game physics and attempting to advance game design:

> Games are primarily educational devices. – And yes, all learning has negative side effects, because all expression presents a subset of reality, and that subset is necessarily misleading in what it leaves out.

Consequently he proposes the following statements to illustrate the challenges faced by each game designer:

> All drama distorts physical reality to foster dramatic reality. ... In our designs, we should seek not realism but clarity. ... You can't really say anything interesting with games.

For Crawford, games really limit reality because they use distortions and appear "hollow" as messengers of truth. Regardless, further research into game design is a worthwhile goal for him, and he strongly believes that computer games have yet to reach their real potential.

Danny Kodicek

Interestingly enough, programmers seem to enjoy "faking" physics. Danny Kodicek is a programmer who produces software for science education that includes physics simulations. He also wrote a foundational book for game programmers entitled *Mathematics and Physics for Programmers* (Charles

River Media, 2005), which explains in detail the mathematics and physics that is needed for modern game development. Since he is familiar with game physics, he has many anecdotes about the topic, such as:

> Magnetic field lines, ... it turned out that calculating these fields was really hard. My field lines kept crossing [and] I only got rid of it by cheating.

and

> The ingenuity of the players in discovering new ways to manipulate their environment can create really interesting results, i.e., the *EverQuest*[39] wardrobe example.[40]

For him game physics and physics acceleration is mostly a limited design tool:

> In the mainstream game world [game physics] is not particularly important except in the simulation genre. ... These engines are used for blowing stuff up.

When confronted with my proposed new game physics elements which include more precision, for example, he counters this with the personal view:

[39] *EverQuest* (Sony Online Entertainment, 1999) is a 3D fantasy-themed Massively Multi-player Online Role-Playing Game (MMORPG).

[40] Kodicek writes: "A gang of rogue carpenters would surround a supposedly immune character and build a wardrobe around them, trapping them inside, and would only release them when paid a ransom. Because the wardrobe was their property, the captured person couldn't destroy it. Now that's a wonderful example of the consequences of using unrealistic physics."

> I'm not a big fan of realism in games. I can get realism outside.

As a software developer, Kodicek follows the traditional belief that game physics needs "faking" because game physics is mainly driven by entertainment. He thinks that improved game physics could be a good game design tool, but refuses to pursue this goal, because he thinks nobody really cares about realism in computer games.

David Bourg

David Bourg's perspective mainly reflects his opinion about the game industry and the game consumer. Bourg wrote *Physics For Game Developers* (O'Reilly Media, 2001), an introductory book primarily about the implementation of rigid body dynamics in real-time games.

> Most people view mathematics and physics as impractical and something they'll never use in the real world.

Based on his direct experience in developing educational game physics algorithms for his book, he outlined the process and future of the field:

> Tuning is the iterative process of tweaking and refining the simulation to get things just right and stable. ... I expect these [physics accelerator] cards to do for physics what graphics cards did for graphics.

When asked about the pseudo game physics that can easily be observed in many games, he provided this explanation:

> All games have some elements of unrealistic physics either by design or by necessity due to other development restrictions. ... Arcade style games often just fake the physics.

Bourg's important comments about the consumer of physics in games are an accurate reflection of the fact that the general public often dismisses physics as impractical. He also points out that game physics has been overly simplified and believes this trend will continue.

Ed Rotberg

Ed Rotberg reflects the views of a game development veteran. Rotberg was the primary force behind the 3D tank game *Battlezone* (Atari, 1980) which is considered the first VR game (see section **??**). He is also an expert in the programming of driving simulators, which typically use the most accurate game physics of any game genre. Based on this unique perspective, he writes:

> The NASCAR simulator [with 6 CPUs] is a marvelous experience. It is not quite like driving a real car, although it is very close. ... The two primary reasons for games eschewing the implementation of real physics are: playability and performance.

On the question about the possible benefits of game physics realism, he provides this suggestion:

> There is a very interesting example of some interesting physics in a game [called] *Strange Attractors*[41]. ... Certainly the physics is not completely accurate.

[41] *Strange Attractors* (Ominous Development, 2006) is a space-themed indie game which was created for a game competition and features an innovative gravity simulation.

However his ambivalence between real and pseudo game physics is clear from the following statement:

> *Battlezone* pretty much had very, very little of what anyone would call "real" physics. ... It is a point of fact that many games will intentionally, knowingly, go out of their way to deviate from real physics.

Although the so called "father" of VR states clearly that virtual *reality* does not guarantee *any* reality in physics at all, Rotberg still believes that good physics can benefit game design by actually improving the experience for the player.

Kevin Ryan

In 1991, Kevin Ryan programmed the well-known and prize-winning game *The Incredible Machine* (TIM) (Dynamix, 1991). This was one of the first commercially successful games based around a detailed game physics engine, and it implemented a Rube Goldberg-style puzzle simulator (see section **??**). When asked about the type of physics in *TIM*, Ryan replied:

> Almost all physical interactions [in TIM] are [based on] just one nice mathematical formula worked out by *Sir Isaac*. Add in gravity and then fake the way that air density works and it is very surprising how rich a set of interactions you can get. ... Ropes are completely fake.

Of particular interest were his comments about the "clockwork" implementation of the Newtonian physics to ensure repeatability:

> Every machine that was built would be deterministic. ... The only random elements in the game are things that do not affect the physics.

As creator of the game, he confirmed that the educational draw of this type of game genre is important because "TIM made its way into many schools." However, what was actually taught is not clear.

For Ryan, physics is an enriching and interactive design element; his particular implementation, however, uses it in a completely deterministic way. Any perceived educational value of game physics in his games was not made by intention. He also confirms that most game physics remains limited or is implemented in a scientifically incorrect way.

Matthew Wegner

Development director Matthew Wegner is also interested in the possibilities of game physics; he started the website *fun-motion.com*[42] as a side project from his day job at Flashbang Studios. This blog site for physics-oriented games contains mostly reviews of productions where gameplay focuses on game physics. Wegner and an informal group of contributors have collected much information on the site over the years, which has allowed him to ascertain:

> Real-world simulation isn't desirable in many games. We are talking about entertainment, after all. ... Nobody wants a game that mimics reality 100%.

Since he is a developer of casual games, he makes a point on the future and breadth of the gaming market:

[42] See `http://www.fun-motion.com`

> Culturally the notion of "gaming" and "gamers" will dilute to the point where games are viewed in the same way that mainstream entertainment is today.

However, he does not believe in the commercial viability of the serious game genre:

> I don't know of any commercial, retail games with an educational agenda.

His example of a game that implements very realistic physics highlights one of the reasons – here the abstract game rules – why such games tend to fail in the marketplace:

> [For example,] *Elasto Mania*[43] is a hugely popular game. ... The physics are very abstracted in what I feel is a very undesirable way.

Wegner prioritizes entertainment and he firmly believes that nobody wants "realism." He also confirmed that any educational value found in existing game physics was often not really intended by the designers or programmers involved.

Max Behensky

When Max Behensky worked for Atari, he was responsible for the programming of one of the earliest sophisticated[44] driving simulators called *Hard*

[43] *Elasto Mania* (Balazs Rozsa, 2000) is a motorbike simulation game based on a real physical model.

[44] The arcade version of *Hard Drivin'* was marketed as *"The World's first authentic driving simulation game"* when it was released.

Drivin' (Atari, 1988). Since then he has worked alongside Doug Milliken, one of the world's leading experts in car modeling software, so he can speak with some authority about the technical depth required to implement proper simulations. He suggests that:

> Accurate car physics is extremely difficult to do. ... The vehicle model took me more than one year of full time work to develop.

He believes that such efforts are very important in game design and offers the following advice:

> Good physics with bad graphics beats bad physics with good graphics every time. ... Getting human body physics right in games would be a major improvement.

However, in relation to the value of such implementations for the consumer, he is much more pessimistic:

> Mathematics (specifically calculus) and physics are perceived by most people as way too hard to understand, and basically useless in real life.

As a practitioner of state-of-the-art game simulations, Behensky confirms, on the one hand, that proper game physics is very difficult to implement; but on the other hand, he thinks that there is great play-value in game physics.

Megan Fox

Megan Fox is a much younger game programmer and designer as well as a musician. She has hands-on experience in applying game engines that include

physics and environmental simulations. What was her motivation to enter game design in the first place? She comments:

> I found [that] I was learning nothing in Computer Science.

Her position as game developer at the beginning of her career led her to make the following pragmatic statements about game physics:

> I'm interested primarily in convincing fakes of physical effects, not realistic representations. ... Movement and environment are solved problems, and the rest can be faked well enough to work within that context. ... So the fight continues to make ever-impressive graphics while still retaining time for basic game design.

When I asked her to suggest uses for games in the sciences, she responded:

> A game could be useful for behavioral and psychological experiments, just not for simulations of the physical world.

As with others respondents, game developer Fox tends to "fake" physics because for her, the primary focus of a game design is all about the entertainment value of the game.

Summary

Based on the above interviews, some common "threads" of reasoning can be observed amongst game developers:

1. Game physics is mostly "faked."
2. Game design is all about entertainment, which requires the avoidance of realism.
3. Science-education (particularly physics) from games is at best an accidental side effect.

The developers' opinions diverge on the following issues:

1. The difficulty of game physics for the implementer.
2. The contribution of game physics as a design element to the game.
3. The potential of computer games to advance media in general.

In conclusion, game developers mirror the general stance of the public towards sciences, and physics in particular, considering these topics uninteresting, useless, and complicated. This attitude leads to a limited use of game physics for highly specific game designs. But is this what the game players really think?

2.5.2 Game Player Survey

To gain a better insight into the perception of game physics from a game player's point of view, an anonymous online survey was conducted by using the *SurveyMonkey*[45] service. In total, the questionnaire contained 34 questions that were targeted towards players of computer games and asked them specifically about game physics topics. The participants were solicited by posting articles on several online forums, blogs and mailing lists[46] as shown in table 2.2. Participation in the survey, entitled "Game Physics and Video

[45]See `http://www.surveymonkey.com`
[46]Mailing list post via D. Kodicek and blog article by M. Wegener (see section 2.5.1).

Game Players," was entirely voluntary. The 2007 survey was launched on January 1st and closed after two weeks, because by then a predetermined number of responses had been received. During this period, 402 unique respondents were recorded with over 200 having completed all questions.

Type	Name	Reference
Forum	PC Gamer Forums	http://forum.pcgamer.co.uk
Forum	Indiegamer Developer	http://forums.indiegamer.com
Forum	Xtreme-Gamer Forums	http://www.xtreme-gamer.com
Forum	Monstergamer	http://www.monstergamer.net
Forum	Inside Mac Games	http://www.insidemacgames.com
Forum	LDA Games	http://www.ldagames.com
Forum	Women Gamers	http://www.womengamers.com
Forum	The Older Gamers	http://www.theoldergamers.com
Forum	Gaming Forums Canada	http://www.gamingforums.ca
Mailing List	Game Developers List	dragon@well-spring.co.uk
Blog	Fun-Motion Article	http://www.fun-motion.com

Table 2.2: Sources of participants for the 2007 survey "Game Physics and Video Game Players" conducted by author

Player Demographics

Who are these players? In order to determine the approximate demographics of the survey participants, several introductory questions asked the respondents about their gender, age, play frequency and game genre preferences.

As can be seen in the age distribution of figure 2.4, the participants were relatively young with an average age of 23 years and predominantly male (an astonishing 96%, see figure 2.5, middle chart). These demographics do not match well with the official statistics of game player demographics that are published by the *Entertainment Software Association* (ESA). ESA's broad survey cites an average age of 35 years for gamers with 40% being female (Entertainment Software Association 2009). However, since online forums were the primary source of volunteers for this survey, a bias towards a young,

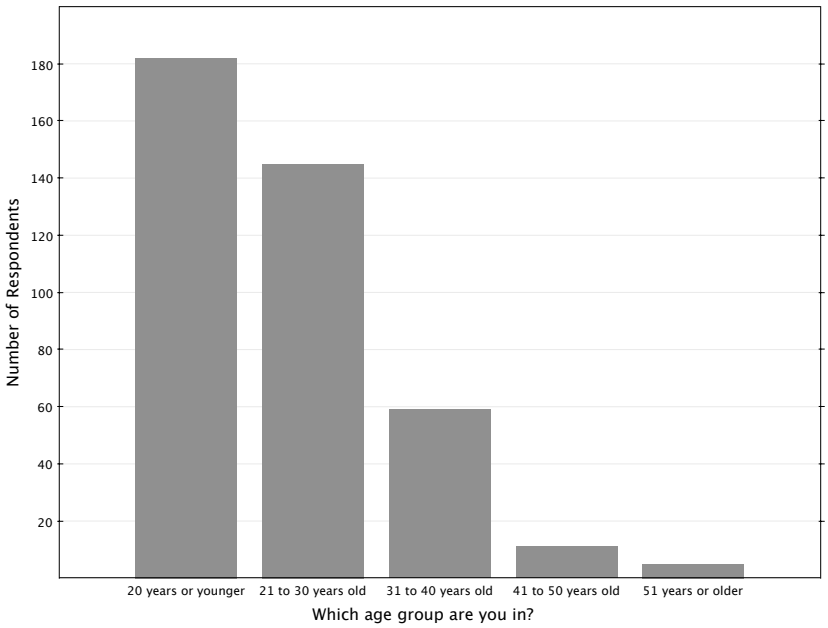


Figure 2.4: Age groups for the survey of game players (402 to 228 respondents)

male demographic was actually expected. A survey question asking players to categorize themselves confirms this, with 57% of the respondents claiming to be *hardcore* gamers who are very knowledgeable about the gaming scene. I am aware of the fact that forums attract a certain gamer persona, which skews the demographics of the survey. This limitation lowers the broad applicability of the results, but does not invalidate this investigation and its analysis.

The survey contained two gender-related questions, asking respondents if they think that there is a gender bias in either games or sciences. Comparing the results in figure 2.5, one can observe a significant perceived difference for this demographic group. The male dominance in computer game design is the accepted status quo for players (left chart), whereas sciences are assumed

to have much less of a male gender bias (right chart). Thus, I conclude that players make a clear conceptual distinction between the domains of entertainment (i.e., game physics) and research (i.e., real physics).

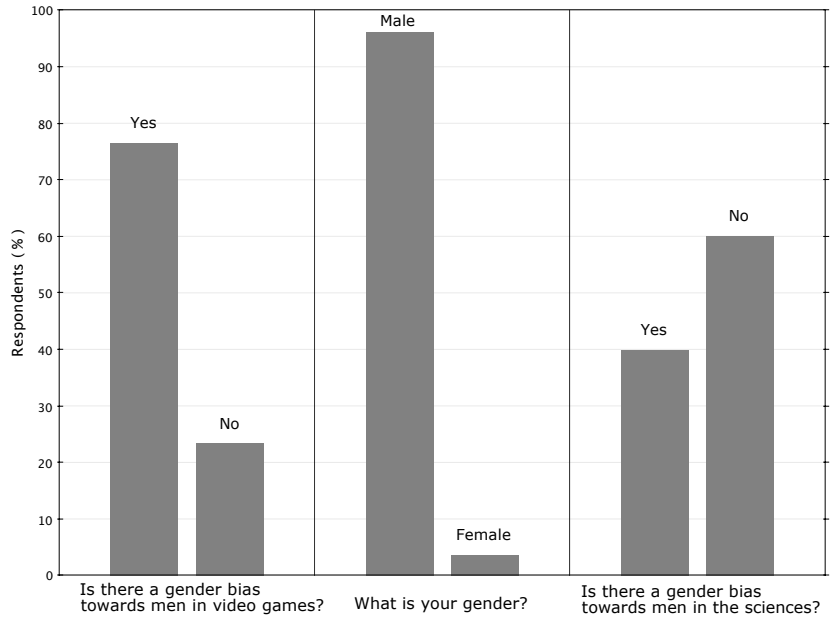


Figure 2.5: Gender distribution and perception of gender bias in gaming vs. sciences from survey of game players (402 to 228 respondents)

Figure 2.6 summarizes the popularity of game genres in the surveyed demographics. The list is topped by the 3D-based action games such as first-person and third-person shooters, which rely heavily on game physics (see section 2.3.2). Somewhat less popular were Role-Playing Games (RPGs) and Platformers, which are genres with less realistic and simpler game mechanics. Simulation games were also evidently much less popular with players, as were serious games and educational software, which rank among the least popular in the list.

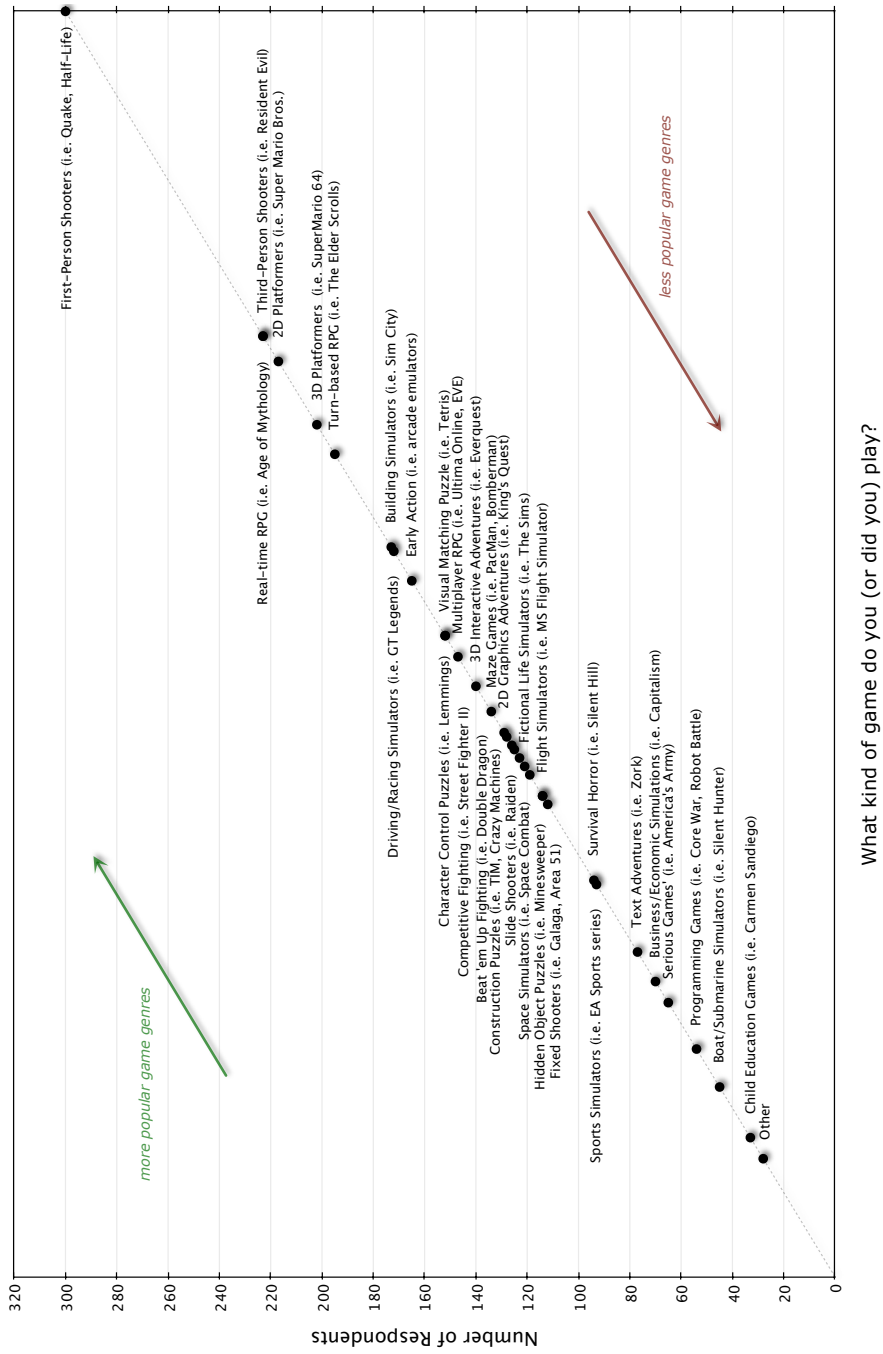


Figure 2.6: Preferred genres of games from survey of game players (332 respondents)

Views of Game Physics

I designed several preliminary questions at the beginning of the questionnaire. These were aimed at determining the player's knowledge and perception of game physics. For example, one question asked the player to rank game elements by their importance. The analysis of the answers indicates that the most desired one is "entertainment value." The other elements highly regarded by players are those that support entertainment, such as a reactive and usable interface, gameplay innovations and good AI.[47] When asked separately to rank the importance of game physics, the rating was similarly high (see Appendix F). This finding is supported by the fact that players are familiar with the game physics types that are commonly provided by the game engines (see section 2.3.4). However, in a followup question, which asked respondents to rank statements regarding game physics (see figure 2.7), the results reveal some confusion. Although Newtonian mechanics was correctly identified as the predominant form of game physics, players did not perceive any benefits from the suggested modes for "better" game physics. They were even quite dismissive about the presence of accurate game physics in simulation games. It should be noted that the text of the survey itself could have caused the observed results, as players might have merely guessed what was meant by some terms used in the questions.

A similar question listing the possible benefits of improved game physics (see figure 2.8) aimed to rank the awareness of players about issues with game physics. Respondents accepted the ideas that pseudo game physics is present, and that better game physics would improve the play experience and might even educate players in the process. The possibility that pseudo game physics might have an impact on them or their perception of science, however, was often dismissed. The suggestion in the survey that adding science to games

[47] AI is generally used to control Non-Player Characters (NPCs) in a game. Good AI makes for example a NPC behave challenging and smart towards the players actions.

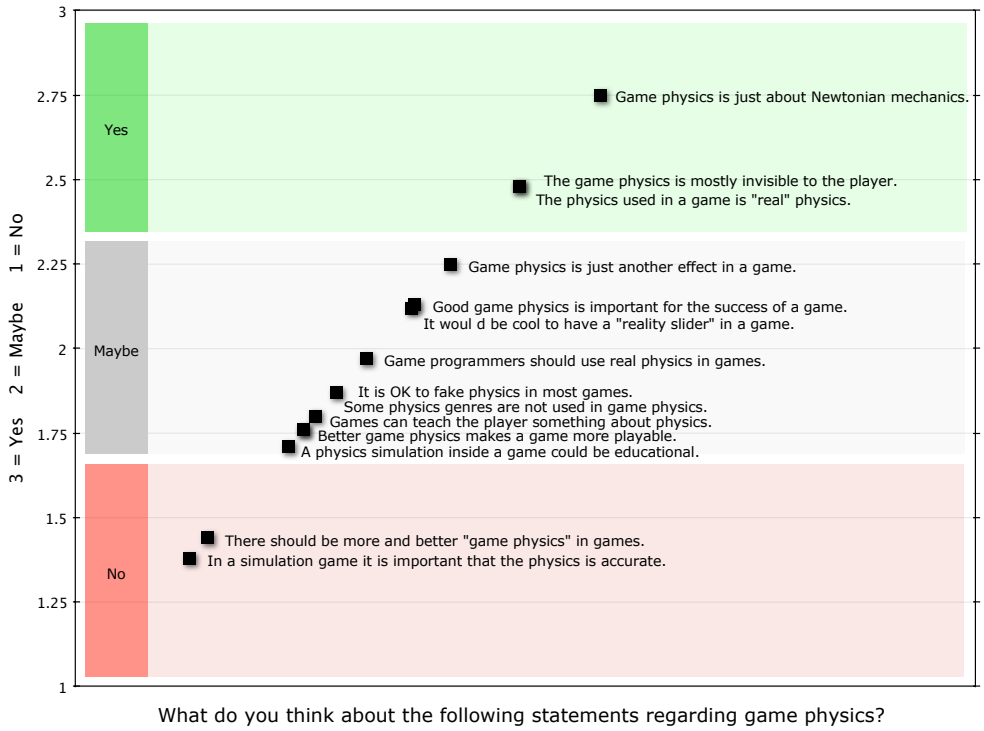


Figure 2.7: Player beliefs about game physics in survey of game players (236 respondents)

might help lower the gender imbalance in gaming was soundly rejected.

In order to obtain valuable information for the development of new game physics elements, the players were asked to agree or disagree with a variety of proposed methods that could improve game physics. As the results show (see figure 2.9), the favorite goal was the possibility of a more convincing alternate reality, from the use of improved game physics. This response is consistent with the traditional entertainment purpose of games in general. In contrast, innovative ideas were much less likely to be accepted, resulting in a clearly visible "acceptance gap" between the in-game experience of a heightened immersion and most other suggestions. While players valued the

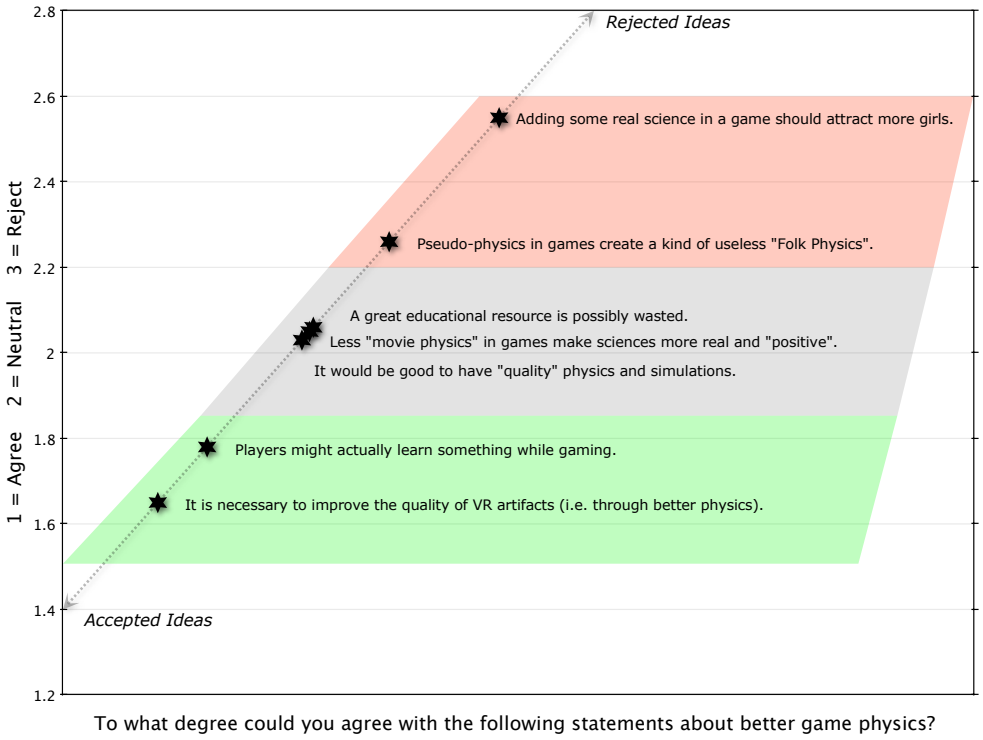


Figure 2.8: Player preferences for the experience resulting from accurate game physics in survey of game players (215 respondents)

ability to perform scientific experiments inside games, they rejected other similar elements that could provide more accuracy and measurability or better documentation about the science involved.

Summary of Player Survey

In conclusion, this survey of a primarily male and young audience of computer game players reveals the following common themes:

1. Science is not perceived as gender-biased.

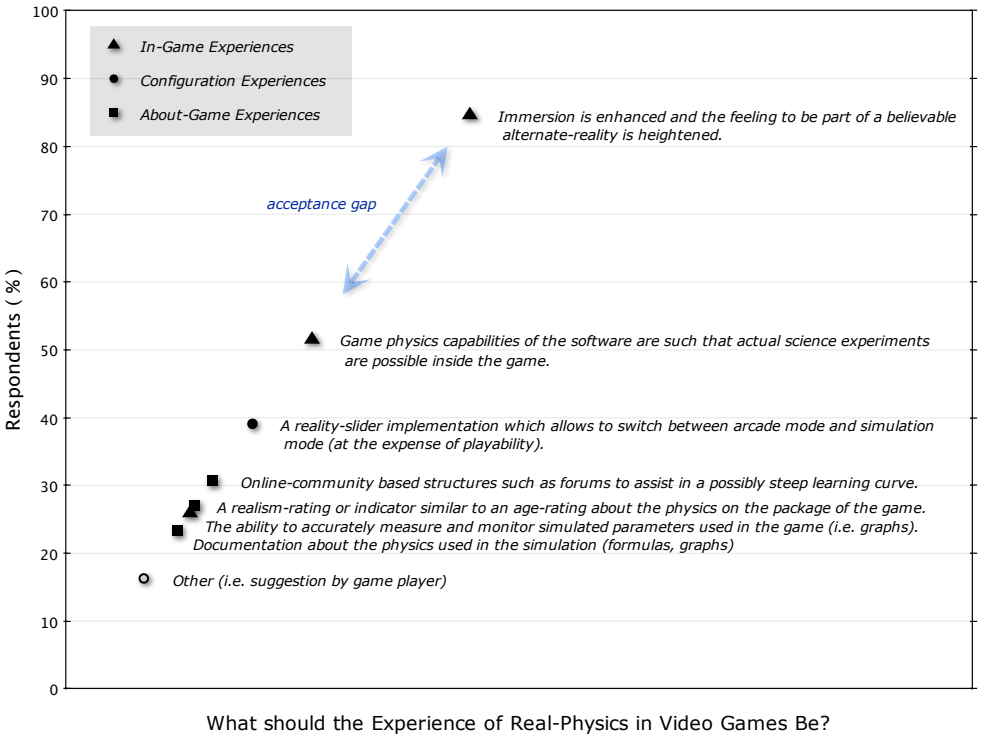


Figure 2.9: Acceptable ideas for accurate game physics in survey of game players (219 respondents)

2. *Shooters* and Platformers are the most popular genres, whereas educational games and simulation genres are relatively unpopular.
3. The interest in practical physics topics is relatively high.
4. The most important game aspects concern the level of entertainment and the depth of immersion.

In relation to game physics, the following results stand out:

1. Players generally like innovative ideas in games. Some of the ideas related to game physics were rated with high acceptance.

2. Players have many misconceptions about the "reality" and breadth of game physics.
3. Players are interested in game-based physics experiments.
4. As "consumers," players are often oblivious to the benefits and effects of improvements in game physics.

I conclude from these results that computer game players should be exposed to the actual implementations of elements. These elements could be derived from novel fields of physics in order to determine if such new game physics might be a viable value proposition for players in the future.

2.5.3 Physicists Survey

This dissertation attempts to investigate the potential of game physics in actual physics research and tries to establish modes of communication between the science and game design communities. Therefore, I have conducted an anonymous online survey about game physics, exclusively targeted to an audience of physicists.

The survey, entitled "Game Physics and Physicists," featured 34 questions and was completed in early 2007. The voluntary participants in this questionnaire were solicited by sending them a personal email that outlined the research and contained a link to the survey. The email addresses were sourced from the online *Global List of Physics Departments*;[48] over 500 emails were chosen at random covering physics departments in many countries. The survey was launched on March 3rd when emails were first sent out, and closed on April 7th after no more responses had been received for one week. In total 44 respondents started the questionnaire and 26 completed the full set of questions.

[48] See `http://www.physnet.de/PhysNet/us.html`

Physicist Demographics

The initial questions in this survey served to establish the demographics of the respondents. Again, as the results of the gender and age questions indicate, responses came from a primarily male audience (93%), with an average age of 37. Most respondents (76%) think that there is a clear gender bias towards men in physics research.[49] All respondents rate their physics and mathematics knowledge as average or higher, an indication that it was indeed the expected target group that completed the survey. Interestingly enough, about half of the respondents associate themselves with research in experimental or computational physics; both fields are quite similar to practical game physics, proving that there is a correlation between the survey topic and the responders' field of work. Even though this group is highly educated, more than 75% rated their knowledge in economics, arts or music as "very basic," indicative of a narrow education and specialization in the sciences. Several questions probed their primary modes of communication about their physics research with the public. The majority (71%) has published in a peer-reviewed journal or conference proceedings, but no one had used interactive media or computer games in relation to their work.

Physics and the Public

A collection of questions was designed to determine how physicists feel their work relates to the public. The majority of respondents thought that although physics affects people's day-to-day life, there is a crisis in science education, and that society needs to provide better physics education for children in the future. For example, a third (38%) of the respondents agreed with the statement: "Science works and produces results, but people think

[49]The fact that there is a lack of female scientists in Physics, has been proven by numerous statistics (Suomen Fyysikkoseura 2008).

most of it is very suspect, incomprehensible or problematic." All respondents agree that movie physics reflects physics inaccurately, and many of them claimed that popular media has a negative influence on the public perception of physics. For example in the general feedback to the survey, one respondent said: "I thought, that I was the only physicist worried about many of these questions." The theme of this dissertation – finding ways to educate the public about physics – seems to be conceptually shared by other physicists. Since I am not aware of any similar research into the effects of games on the public perception of physics, such conclusions verify that this study is an important topic and may provide value to physicists.

Reflections on Game Physics

The majority of the survey questions were designed to gauge the knowledge and beliefs of the physicists about games and game physics. While the analytical results derived from some questions may not be statistically significant due to the relatively low number of respondents with computer game experience, they still provide valuable insight into how physicists may think about the topic of computer games and game physics.

As expected, the expertise about games and game physics in this group of respondents is significantly less than that of the surveyed game players (see section 2.5.2). Over half (54%) of the physicists have little exposure to this form of entertainment, and 56% have never heard of "physics engines" or "physics accelerators." However, this self-declared lack of knowledge seems to be a conscious choice by the respondents, since 89% claim to have used the PC as a gaming platform, and most respondents could describe game physics correctly as a dynamics simulation when asked. This is an indication that physicists are decidedly *not* interested in game physics. Compared to game players, the explanations given for the term *game physics* by physicists are

more varied, and range from sophisticated statements to mere guesses. For example, one posited that game physics is "the accurate, as filtered by visual and auditory perception, depiction of the laws of motion, electromagnetic, optics, thermodynamics, materials properties, and similar realizable macro scale phenomena." Another guess referred to "tests of physical intuition." There also existed a genre preference for realistic game-world simulations in this group, with driving simulators being the most popular and first-person shooters a close second.[50]

When those surveyed were asked about different potential benefits of improved game physics, over 90% of physicists agreed with the statement, "It is important to experiment [in a game]; trial-and-error is a viable method for doing research in physics." Thus, respondents strongly believed that game physics could be an educational tool by allowing experimentation inside the game. However, other responses point to the prerequisites the player would need for such experimentation; simulations need to be made accurate and game designers should first start to deploy more realistic physics in their games. One respondent stated, for example, that for VR to be useful in science education, "The physics there has to be well-represented, or it isn't realistic or beneficial as a training tool." As reply to the related question, "Can an interactive multimedia art installation become *physics*?" the scientific quality of the implementation was cited as the key differentiator in such a categorization. I agree with this assessment, because such qualities are characteristic to physics (see Appendix F).

The respondents provided several usable suggestions for new game physics topics in the open-ended response section. These included the use of game consoles as a computational resource in science experiments similar to the

[50]Several respondents even knew the game *Half-Life 2* (see section **??**) when asked about it in a specific question.

Seti@home[51] project, the simulation of a scanning-probe microscope, sand flow simulations, a long-term space flight simulator, and even the creation of "a new *virtual* universe embedded in a real machine." However, as one respondent pointed out, a fundamental limitation of such game physics is that the outcome of any simulated experiments would be predictable because "quantum mechanical features, such as uncertainty, or aspects of reality yet unknown to us are hardly programmable *today*." In my view, these very limitations are the ones that new game physics should seek to address.

Summary of Physicist Interviews

The most striking result from the survey was the low response rate of only about 4% of the emails that were sent out.[52] Several other personal email communications with the physicists about this research provided similar observations and point to significant conceptual barriers that physicists must overcome in order to engage with this study on any level. These barriers have manifested themselves in a range of responses, from a general disinterest in a survey through non-participation, to an outright verbal rejection to collaborate in any research that involves computer games.

Nevertheless, the presented survey was at least partially completed by 44 physicists and provided these key observations:

1. The subjects of this study were primarily male, with a large age spread. A significant representation of scientists in the applied fields of experimental and computational physics participated. They all admitted to a self-assessed poor knowledge in non-scientific fields like art.
2. The bulk of the publications by physicists lie within the sciences and

[51] See `http://setiathome.berkeley.edu`
[52] Clicks on the survey link in the email are tracked to calculate the response rate.

their peer-groups, even though the impact of physics on the public is seen as very important.
3. The surveyed group assumes that the public's perception of the sciences is negative, but respondents had mixed beliefs about the origin of this perception and whether popular media plays a positive or negative role.

Not many physicists play computer games; but the ones who do, respond in a similar way to the game players (see summary of section 2.5.2). However, the following themes do differ:

1. The two preferred physics elements were (a) conducting experiments inside a game and (b) a "reality slider" which would allow games to be set to more accurate simulations.
2. While accuracy is generally desired, advancing the goal of educating the public at the expense of accuracy, while not preferable, is considered *acceptable*.
3. Elements that were rejected by game players but accepted by physicists were: the addition of physics documentation to games, and a proposed "physics realism rating" for games.

2.6 Chapter Conclusion

The results of the above research clarify the scope of the term *game physics* and demonstrate that the use of physics in computer games may play a role in how game players perceive physics as well as how scientists perceive games. This analysis will be applied in chapter 5 to define several principles for physics-based game element design.

The science of physics is a collection of effective theories split into the two general subsets of classical and modern physics. These can be further

differentiated into many subfields of physics and represented as a Venn diagram of overlapping central theories, which share common features. Four key characteristics are identifiable across all fields of applied physics: the use of the scientific method, the belief in an underlying unity of nature, the reliance on the language of mathematics, and the pursuit to increase the precision of experimental results. This study also highlights some issues physicists face today. It can be shown (see Appendix B) that a widespread public perception of physics is that it is merely an intellectual exercise. Physicists face an enormous challenge to explain the classical vs. modern physics dichotomy, and they are often involved in unresolved debates on how to make progress toward future understanding in the public realm. Section 5.2.1 will reflect on these ideas and propose principles that can make game elements more scientifically relevant and potentially allow game players to understand physics better.

In contrast to the more theoretical science of physics, the use of physics-based simulations in computer games is an applied, practical topic, which can be described as a game design element. Commonly known as *game physics*, this design element can be found as specializations of aesthetics, game mechanics, story elements or technology present in game designs, and it is required for certain types of games such as 3D genres. As the analysis of the implementation process of game physics presented here indicates, game physics simulations do not usually reflect real behavior, but are almost always simplified to provide real-time responses to game users or meet player expectations.

Types of game physics found in current computer games include the simulation of light and sound, physical interactions of objects within the simulated space, and narratives involving physics. A survey of the technical literature on computer games shows that only the design element of object dynamics simulations is considered as game physics by game developers. Technological

advancements and the common use of game engines increase the fidelity and scale of object dynamics simulations, but also narrow the game physics scope to a single field and do *not* fundamentally advance this design element.

My survey of game physics designs in games released from 1978 to 2006 (see Appendix C) clearly indicates that game physics repeatedly diverges from "true physics" in several ways. The proposed term *pseudo game physics* is coined to describe this phenomenon. The limited field coverage of dynamics, acoustics and optics found in traditional game physics constitutes one form of pseudo physics; other forms include the inaccurate use of terminology as well as the inherent simplification introduced by disregarding most aspects of modern physics. There exists also a lack of precision in many computer game simulations of physics, and this was found to be a deliberate design choice by the game developers. Such implementations conflict with the needs of educators and scientists and effectively lower the inherent quality of the simulation. Furthermore, the simulated values in game physics are in almost all cases inaccessible to the player, thereby inhibiting any application of the scientific method to game simulations of physics. Unfortunately, physical hyperrealities are created when game physics modifies physical laws for entertainment needs. Such game-physics-driven hyperrealities can be observed in computer games and were found to influence player behaviors. These together with many other incorrect physics metaphors introduced into game designs, including the transposition of "movie physics," also constitute a common type of pseudo game physics. I will propose several principles of game element design in section 5.2.2 which are specifically targeted to resolve such shortcomings.

The study determined, through the analysis of interviews, that game developers treat game physics as a highly specific game design element which they use to further their entertainment goals. Sadly, they only perceive a need to match the expectations of the consuming public (i.e., game players),

identified as the increase of immersion and entertainment value. Topics in general science or physics are largely treated as being uninteresting, useless, and complicated, thus of no use in game physics. Game consumers reflect this view. However, in contrast they do see value in innovative ideas of new game physics designs, especially when related to practical physics topics. The survey of players also provides evidence that there are strong misconceptions about physics and game physics, a further indication that the level of education and understanding of physics is problematically low. The attempt to survey physicists in the context of a study involving mass media entertainment such as computer games was largely rejected by the target group. This result suggests that a significant conceptual barrier also exists for physicists. They would need to overcome these views, if they want to transfer some ideas about physics to the public through the medium of computer games. These collected observations from all practitioners can provide value in informing the design of new game physics elements, a goal I have explored in section 5.2.3 of this dissertation by defining additional principles for game element design.

Chapter 3

Quantitative Analysis

3.1 Introduction

This chapter provides an in-depth quantitative analysis into how game physics has been used in computer games over time as well as across gaming genres and platforms. By doing so, the chapter attempts to answer the following questions:

- How pervasive is game physics in computer games?
- Has the use of game physics as a design element changed over time?
- Does game physics depend on external factors such as technological advances or the type of game platform?
- Can one infer design goals based on the way game developers integrate physics?

3.1.1 Validation of Methodology

I propose that averaging data across many games and game genres is a valid methodology. This statistical approach can be used because the size of the computer game industry is significant and produces a steady stream of new products every year, which generates a sufficiently large sampling set.

Games are a common form of entertainment and their pervasiveness is reflected in the number of computer games sold every year. The game analytics company VGChartz Ltd (2010) maintains a comprehensive database of commercial games published since 2005. The publicly available list includes the total sales volume per game. Aggregating these numbers for the top 500 games over 5 years[1] shows a total of 2,361,480,000 games sold. The actual distribution of games amongst consumers is even higher, since the sales figure does not include legally shared or re-sold games, plus an estimated 35% more illegal copies (Siwek 2007), as well as an unknown percentage of game titles found in the "long tail" of lesser known games which are not tracked in this database.

Therefore, the following agenda assumes that game players worldwide acquire at least 500 million game units each year, which is indicative that the market is served by a very wide range of computer game types. Since the diverse products developed by the game industry reach such a huge audience in large numbers, a statistical analysis of games is a valid methodology.

3.1.2 Influences of Technological Advances

The quantitative analysis that follows will consider variations over time. Since the computer game industry is based on technologies that undergo

[1] January 2005 to March 2010

rapid cycles of advancement, the influences of such hardware changes need to be considered as well.

Table 3.1 summarizes the hardware specifications of popular game platforms from 1975 to 2010. One can clearly see that game platforms have undergone tremendous technological improvements in the areas of CPU speed (4-5 orders of magnitude), memory capacity (5 orders of magnitude) and graphic resolution (2 orders of magnitude).

Platform	CPU (MHz)	CPU (Bits)	Memory Size	Graphics Resolution	Units Sold	3D
C64	1	8	64K	320x200x4	17M	
Asteroids	1.5	2x8	2K	256x231x15	70K	
NES	1.8	8	2K+ROM	256x224x4	61M	
ZX81	3	8	64K	256x192x1	1.5M	
MSX	3.5	8	64K	256x192x4	5M	
ZX Spectrum	3.5	8	48K	256x192x4	100K	
SNES	3.5	16	128K	512x224x8	49M	
Gameboy	4.2	8	8K	160x144x2	118.7M	
Amiga	7	8	512K	640x256x8	4.8M	
Atari ST	8	16/32	512K	320x200x4	1.5M	
Neo-Geo	12	16/32+8	64K	320x224x16	-	
CPS-2	16	16/32+8	4K+ROM	348x224x12	-	
PlayStation	33.8	32/64	2M	640x480x24	102M	✓
PlayStation 2	295	64/128	32M	1280x1024x32	140M	✓
iPhone	412	32	128M	320x480x18	42.5M+	
Blackberry	642	32	128M	480x360x24	50M+	
Wii	729	32/64	88M	720x480x32	67.5M+	✓
Xbox	733	32/64	64M	1280x1024x32	24M	✓
Xbox 360	3200	3x64/128	512M	1920x1080x32	39M+	✓
PlayStation 3	3200	8x64/128	256M	1920x1080x32	33.5M+	✓

Table 3.1: Advances in game platform hardware (CPU, memory, graphics); source: `http://en.wikipedia.org`

Once 3D acceleration hardware became available, graphics rendering speeds also increased significantly since their introduction into the consumer mar-

ket around 1996.[2] Table 3.2 summarizes the evolution of a key component of the graphics rendering pipeline, the *pixel shader*. Pixel shaders are hardware components that provide functionality to compute color, translucency and other attributes for each pixel while they are drawn. They are often used to simulate optical properties of the game world such as specular highlights; they "create ambience with materials and surfaces that mimic reality." (Nvidia 2010) Again, an increase in the capabilities of graphics cards of several orders of magnitude, as illustrated by the pixel shader component, has occurred in less than a decade.

In summary, computer game technology has advanced significantly over time. The analysis that follows in section 3.4 must take such advances into account, in particular when reviewing time series spanning more than 10 years.

3.2 Categorizations of Computer Games

Computer games are an area of gaming in their own right and a relatively recent phenomenon in our culture. Arguably the first such game was *Spacewar*, created by Russel in 1962, which evolved as a spare-time software development on scientific computer equipment (Levy 1984). Since that time, many more games have been designed and published. The most common genre, from the time of the conception of living-room computer games with *Pong* (Atari, 1972) to today's violent 3D-shooters, involves games which emphasize hand-eye coordination, called *Action Games*. But there are many other classes of computer games, including new ones containing social elements, made possible by the availability and ubiquity of the global Internet. There are also many crossover genres that combine features from more than one

[2]High-performance hardware-accelerated 3D graphics became available for games on the PC with the release of the *Voodoo Graphics* device by 3Dfx Interactive Inc. in 1996.

Manufacturer	Chipset/Device	Year(s) Available	# of Shaders
ATI	R100	2001 - 2003	2 - 4
Nvidia	GeForce3	2001	4
Nvidia	GeForce4	2002 - 2003	2 - 4
Nvidia	GeForce5	2003 - 2004	2 - 4
ATI	R300	2003 - 2004	4 - 8
Intel	GMA	2006 - 2010	8 - 12
ATI	R400	2004 - 2005	8 - 16
Nvidia	Geforce6	2004 - 2006	2 - 16
Nvidia	GeForce7	2006 - 2007	4 - 24
ATI	R500	2005 - 2007	4 - 48
Microsoft	Xbox360	2005	48
Nvidia	GeForce300	2009 - 2010	16 - 112
Nvidia	GeForce8	2007	8 - 128
Nvidia	GeForce9	2008	16 - 128
Nvidia	GeForce200	2009 - 2010	16 - 240
ATI	R600	2007 - 2009	40 - 320
Nvidia	GeForce400	2010	352 - 480
ATI	R700	2008 - 2009	80 - 800
Nvidia	Tesla	2008	128 - 960
ATI	R5xxx	2009 - 2010	720 - 1600

Table 3.2: The evolution of pixel shader units available in consumer GPUs from 2001 to 2010 (Advanced Micro Devices Inc. 2012, Intel Corp. 2012, Nvidia Corp. 2011)

class or sub-class of a game taxonomy. The following section is an attempt to provide a comprehensive classification system for computer games – a taxonomy that is heuristic in nature – by reviewing existing taxonomies, combining their best attributes and deriving a set of game categorizations that can be used to evaluate game physics usage within each genre.

3.2.1 Existing Taxonomies

Many varieties of games pre-date the availability of digital technology, since *play* is an integral part of our culture. So are there any historical taxonomies of games that can be used to organize computer games? In the 19th century, Smith (1831) gave a comprehensive overview of games organized along a historical timeline. He traces the origins of games to those played by Jews, Greeks and Romans and lists game categories such as drama, board games, public games (Olympic, gladiatorial), field sports (hawking, archery), bull-fights and animal baiting, dancing, juggling, and "sedentary amusements" (music, cards, chess). The problem with this list is that it lacks clear categorizations and analysis. Still, the text provides a good perspective of the wide range of activities that can be considered as games. Many publications on games take a different approach and focus exclusively on specific genres of games from a historical perspective. An example is *The Book of Games* (Botermans 2008), a tome that describes the history and rules of over 60 games in meticulous detail. The book covers only "board-games" while leaving out any other types of games. The well-known game theorists Huizinga and Caillois also provided classifications of games before computers had been developed. Their focus is a cultural one and places *forms of play* much more on a continuum of activities. In *Les jeux et les hommes*, Caillois (1962, chap. 2) points out that the "current usage [of classifications] sufficiently demonstrates the degree of hesitance and uncertainty [since] several classifications[3] are employed concurrently" and proposes that just four main forms should be considered.[4] Overall, it seems that the historical classifications are either too broad or too narrow to be relevant in a taxonomy of computer game genres.

[3]Caillois lists the following: the implement used, the qualifications required, the number of players, the game atmosphere and the place of competition.

[4]Competition, chance, mimicry, and vertigo; see section 4.2.3.

The physicist Crawford, who later became a noted computer game designer, was one of the first writers of the digital era who published a complete taxonomy of computer games. In the book *The Art of Computer Game Design*, Crawford (1982, 1984) presents a theory of computer games and argues that one "can learn a great deal about game design by establishing a taxonomy of computer games." His approach is to contrast common factors within game families against their "critical differences," to reveal underlying principles of game design. At a high level, Crawford's taxonomy consists of two categories – *Skill-and-Action* games and *Strategy* games – which contain 6 subcategories each as shown in table 3.3. In the text, the characteristics of each subgroup are described and supported with a list of sample games as well as some game screenshots.

There are several shortcomings with Crawford's categorization. Exemplary games for many subcategories are predominantly draw from Atari games, his employer at the time, while others lack examples altogether. Also, the subcategory "paddle"[5] seems orthogonal to the others dimensions which are either gameplay types (maze, chance, interpersonal) or game settings (sports, race, war). He observes that "much creative opportunity remains in the strategy games field," which reflects his personal preference towards this genre as much as the state of the game industry at the time, which was still dominated by arcade consoles. The chapter ends with the closing remark that "new taxonomies must be created to reflect the changes in the marketplace in the next few years." There is one key observation contained in Crawford's taxonomy that is applicable to the practical portion of this research. Successful games seem to be created in only a few categories through a process where "the archetypical game was followed by several successor games ... until one game hits the nail on the head," indicating that a highly iterative design process leads to both advances in the game design as well as commer-

[5] A "paddle" is a type of input device used in the first successful commercial computer game *Pong* (Atari, 1972), which allows 1D motion control by turning a knob.

Category	Subcategory	Example Games
Skill-and-Action	Combat	Star Raiders[a] Spacewar[a] Asteroids[a] Missile Command[a] Space Invaders[b] Galaxian[c]
	Maze	PacMan[d] Maze Craze[a] Jawbreakers[e]
	Sports	-
	Paddle	Pong[a] Breakout[a] Chicken[f] Warlords[a]
	Race	Downhill Challenge[h] Night Driver[a] Match Racer[g]
	Miscellaneous	Donkey Kong[i] Frogger[j] Apple Panic[k]
Strategy	Adventure	Time Zone[e] Deadline[l] Adventure[a]
	D&D	Temple of Apshai[m] Ali Baba and the Forty Thieves[n]
	War	Blitzkrieg[o] Waterloo[o] Afrika Korps[o] Computer Bismark[p] Tanktics[q]
	Chance	-
	Educational	Hangman[a] Hammurabi[s] Scram[q] Rocky's Boots[r]
	Interpersonal	-

Game publishers: (a) Atari Inc., (b) Taito America Corp., (c) Midway, (d) Namco, (e) On-Line Systems, (f) Synapse Software, (g) Gebelli Software, (h) Microids, (i) Nintendo, (j) Konami, (k) Brøderbund Software, (l) Infocom, (m) Automated Simulations, (n) Quality Software, (o) Avalon-Hill Game Company, (p) Strategic Simulations Inc., (q) C. Crawford, (r) The Learning Company, (s) Richard Merrill.

Table 3.3: Overview of the *Taxonomy of Computer Games* developed by Crawford (1982, chap. 3)

cial success. Similarly, the design of new game physics elements may need to go through several iterations until an element design has reached a sufficient level of refinement to be broadly accepted by players. In summary, according to Crawford, the incremental game design process is confined within specific genres; and while his category/subcategory structure provides a highly useful organizational scheme, the dynamic nature of game technology driven by technological progress necessitates a constant review of existing taxonomies.

The *Gamasutra* website, a winner of the Webby Awards (2007) with the acceptance speech entitled "Art plus science, still games!" is a well known online portal for game designers and has published an article by Lindley (2003) with an updated taxonomy. One could ask if and how this version improves on earlier taxonomies such as the one by Crawford. Lindley's research focuses on developing methodologies for game and interactive narrative design, game semiotics and game form. For such a detailed game analysis, a simple hierarchical system of categories and subcategories is rejected based on the argument that "developing a basic language for describing different types of games requires different dimensions of distinctions." He then proceeds to differentiate game types into a system of three *orthogonal taxonomies* with the following dimensions: gameplay, narrative and simulation. The first taxonomy uses the ludological definition of games, such as the ones given by Frasca (1999), and differentiates game types by their *gameplay gestalt*, which is based on the patterns of interaction within the rules of a goal-oriented game system. The second taxonomy differentiates games by focusing on the *narrative structure* imposed on gameplay rather than their *gestalt*. Lindley describes a narrative "as an experience that is structured in time" such as the three-act restorative structure[6] which dominates film, and points out that in many computer games a highly competitive tension exists between the gameplay and narrative design elements as they compete for player attention. The third taxonomy is based on the degree of *simulation* present in the game. For Lindley, simulation is a representation of the features of one system through the use of another. He posits that games implementing such "prosthetic reality" may neither posses goal-oriented gameplay nor any temporal structure to create a narrative. These three forms are then placed at the corners of a triangle to form a 2-dimensional *classification plane*. As

[6]The definition *Standard Structure* for film is based on Aristotle's three act dramatic structure components of beginning, middle, and end. It is also known as *Three Act Restorative Structure*, because the story begins with an order that is disturbed, and by the end a new restoration of order is reached.

exemplified by figure 3.1, the proposed taxonomy is applicable to many computer games and types, but it is not clear how game physics may fit into such a scheme.

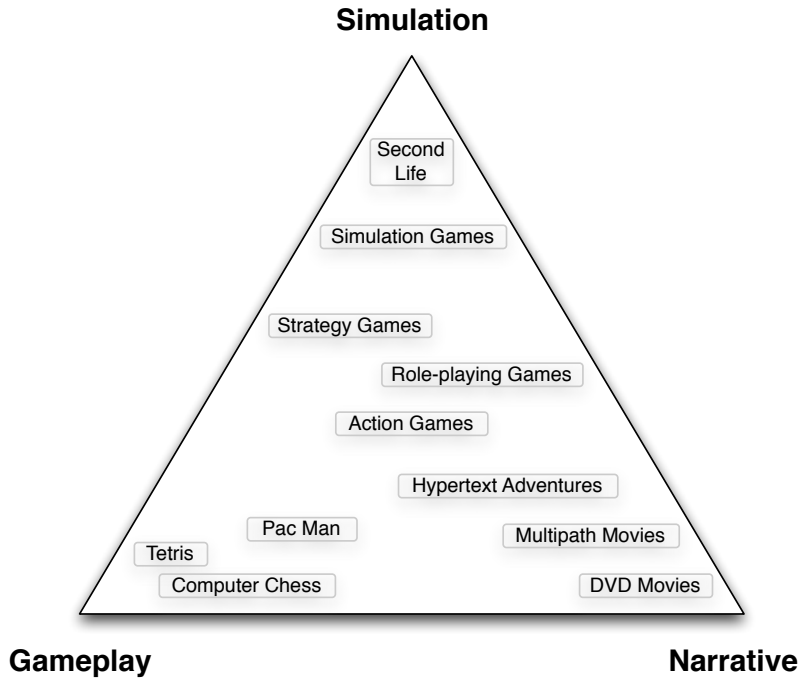


Figure 3.1: Computer game taxonomy based on a 2D classification plane; diagram adapted from Lindley (2003, p. 2)

This limitation stands out when Lindley attempts to incorporate the common game element of "chance," a natural phenomenon rooted in physics, into his scheme. He deems chance incompatible with either simulation or gameplay rules. In order to resolve this shortcoming, Lindley proposes two additional classification spaces, one that draws out the 2D triangle into 3D prisms along a new dimensional axis of fiction vs. non-fiction and another between the virtual vs. the physical. This modification unnecessarily com-

plicates the taxonomy in an effort to broaden its applicability.[7] Nevertheless, one observation can be made which is useful to this research on game physics. Lindley notes that the spatial organization supports brainstorming for game design ideas and allows a game researcher to "see where techniques from other fields can be applied." This perspective validates the approach of section 2.4.1, which attempts to locate potential areas of new game physics through a Venn mapping of field coverage of standard game physics.

There are numerous other efforts to create game taxonomies, which offer even more ways to segment game types. In the text *Genre and the Video Game* Wolf (2001, chap. 6) uses the approach of equating "video game" with "film" to formulate a more traditional genre study patterned after the Library of Congress' *Moving Imagery Genre-Form Guide* (Dutkiewicz 2010), while noting the need to define an "iconography of interactivity" for games. The resulting list of 42 genres[8] has been criticized because of its large size (Järvinen 2002) which is caused by an over-segmentation and the introduction of questionable categories such as *Diagnostics* or *Utilities*. A taxonomy was also developed by the *Institute of Play* during the development of *Game Bucket*, "an online interactive tool for teachers, parents and students" (Institute of Play 2007). Its game database uses a taxonomy composed of an extensive system of hierarchical "tags" attached to each game (Salen 2008). The approach of adding multi-dimensional metadata to the game database limits the taxonomy to its use in search engines and interactive queries. This

[7] The 3D axis of *fiction/non-fiction* and *virtual/physical* are introduced by Lindley, to be able to categorize non computer game types such as Live Action Role-Playing (LARP) games, location-based technology assisted games, military vehicle simulators, team or adventure sports and game shows.

[8] The genres covered in Wolf's taxonomy are: Abstract, Adaptation, Adventure, Artificial Life, Board Games, Capturing, Card Games, Catching, Chase, Collecting, Combat, Demo, Diagnostic, Dodging, Driving, Educational, Escape, Fighting, Flying, Gambling, Interactive Movie, Management Simulation, Maze, Obstacle Course, Pencil-and-Paper Games, Pinball, Platform, Programming Games, Puzzle, Quiz, Racing, Role-Playing, Rhythm and Dance, Shoot 'Em Up, Simulation, Sports, Strategy, Table-Top Games, Target, Text Adventure, Training Simulation, and Utility.

is a useful feature for a game researcher, but makes it difficult to apply to the aggregating methodology proposed by this study. In another taxonomy, Bartle (1999) has analyzed Multi-User Dungeon[9] (MUD)-style games using a system which describes four distinct types of players: achievers, explorers, socializers, and killers. He proposes an *Interest Graph* where each player type is situated in one of the quadrants: "the x-axis goes from an emphasis on players (left) to an emphasis on the environment (right) [and] the y-axis goes from acting *with* (bottom) to acting *on* (top)." This taxonomy is then used to investigate player interactions and to suggest game design elements as well as methods that influence the gameplay dynamics towards particular types of players. Lewis et al. (2007) use yet another approach based on decomposing the development process of a game into three groups: content (art team, sound engineers), mechanisms (design team, script writers) and technology (game and engine programmers). By applying a multidimensional scaling technique, they map games onto a cluster-diagram and find that "players today discriminate along independent content (aesthetic) and mechanics axes, creating some clusters that match traditional genres but many that do not." The visualizations of the complex transformations used indicate that the players' mental spaces of games is much richer than the limited combinations of the traditional genres. Lewis et al. suggest using this information for recommendations that subvert the genre system, although they admit to have introduced bias through their selection of games in the study. Lastly, many of the commercial game portal websites catering to the game-consumer contain the aforementioned sets of "traditional" categorizations. *Gamespy*[10], *Yahoo! Games*[11] and *Gamespot*[12] all use a top-level menu structure of game

[9] A *Multi-User Dungeon* is a multi-user real-time virtual world, played using a text or graphical interface, modeled after the fantasy role-playing game Dungeons and Dragons. The acronym originated from a game published by Trubshaw (1978) of the same name (Kelly & Rheingold 1993).

[10] See `http://www.gamespy.com`, IGN Entertainment Inc.

[11] See `http://videogames.yahoo.com`,Yahoo! Inc.

[12] See `http://www.gamespot.com`, CBS Interactive Inc.

platforms followed by a genre submenu containing between 10 and 30 entries of game types. Similarly the growing number of online application marketplaces use simple classification lists to allow customers to find games. The *iTunes App Store*,[13] for example, uses 20 categories in its "Games" section.

One can conclude that a re-categorization of computer game genres is useful for this research, since many existing taxonomies are likely outdated due to the dynamic nature of game design, as mentioned by Crawford. Additionally, the highly domain-specific uses of most current taxonomies and the fact that game physics was briefly mentioned in just one taxonomy,[14] do support the case of defining a new list of computer game genres for this study. The following attributes of existing taxonomies are used to propose a list of game categories that should be sufficiently useful for analyzing game physics:

- A category/sub-category structure, since it matches well with historic and current taxonomies.
- An indication of the simulation and narrative character, since they are important dimensions for games in general.
- Additional dimensions for content, mechanism and technology, which create valid domain-specific subcategories.
- Examples of games in each category for illustrative purposes, since all presented taxonomies use such an approach.

3.2.2 Proposed Categories for Research

A descriptive taxonomy of computer games specifically developed to evaluate game physics elements is included in Appendix D of this dissertation and

[13] See `http://www.apple.com/itunes`, Apple Inc.

[14] Only Lewis et al. (2007, fig. 1) uses a game physics dimension in his manifold-mapping technique.

summarized in table 3.4. Besides listing the category and subcategory of each game type, the table adds columns indicating the primary dimension of the subcategory (historical, content, mechanism, technology), if 2D or 3D graphics are present, and if simulation or narration play an important role in the genre.

I am aware of the fact that the presented taxonomy has some limitations and shortcomings. As documented in Lewis et al. (2007), a "traditional" genre list does not seem to match the mental models of today's sophisticated game players, nor does it assist a game designer in the game development process. However, the broad use of mobile devices and browsers as game platforms means that many games remain simple,[15] and therefore the traditional genres are still highly relevant. Several genres such as adult games, art games, Christian games, advertising games, and genres for specialized input devices (i.e., paddle or light-gun) are not incorporated into this list due to their limited availability and use. In conclusion, the taxonomy will be used as reference throughout this study; but more importantly, it will be improved upon in section 3.3, which attempts to quantitatively measure the game physics prevalence by genre. Since the data source of this analysis uses commercial and historical game categories, a "traditional" list-based taxonomy is well suited for the research.

3.3 Game Physics Index

Whereas section 2.3 has described game physics qualitatively, this section will propose a method for the quantitative evaluation of game physics in games. Since there exist hundreds of thousands of computer games running

[15]This category of games if often called *casual*, comprised of games which are characterized by their simple rules, limited strategy and shallow learning curve (Boyes 2008). The genre list applies to casual games, although many would not make good casual games.

Category	Subcategory	Dim.	2-D	3-D	Nar.	Sim.
Action	Early Action	H	✓	✓		
	Maze	C	✓			
	2D Platform	T	✓			
	2.5D Isometric	T	✓			
	3D Platform	T		✓		
	Fixed Shooter	C	✓			
	Slide Shooter	C	✓			
	Fighting	C	✓	✓	✓	✓
	First-Person Shooter	C		✓		✓
	Third-Person Shooter	C		✓		✓
	Survival Horror	C		✓	✓	✓
	Rhythm	C		✓	✓	
Strategy	Turn-Based	M	✓	✓	✓	
	Real-Time	M	✓	✓	✓	
	Multiplayer-Online	M	✓	✓	✓	
	Artillery	M	✓	✓		
	Building	C		✓		
	Fictional Life	C	✓	✓	✓	
	Economic	C	✓	✓	✓	✓
Adventure	Text Adventure	H			✓	
	2D/Media Adventure	T	✓		✓	
	3D Adventure	T		✓	✓	✓
Puzzle	Visual Matching	M	✓	✓		
	Hidden Object	M	✓	✓		
	Character Control	M	✓	✓	✓	
	Construction	M	✓	✓		✓
Educational	Child	C	✓		✓	
	Serious	C	✓	✓		✓
	Programming	M	✓			
Simulation	Early Space	H	✓	✓		✓
	Early Sports	H	✓			✓
	Early Race	H	✓	✓		✓
	Flight/Space	M		✓		✓
	Vehicle	M		✓		✓
	Boat/Submarine	M		✓		✓
	Sports	M		✓	✓	✓

Dim. = Dimension of Subcategory: H = historical, C = content, M = mechanism, T = technology,
Nar. = Narration present, Sim. = Simulation present

Table 3.4: Computer Game Taxonomy for Game Physics Analysis

on hundreds of different computing platforms, it would be impossible to analyze each one of them for their game physics content individually. The approach is therefore to first assign an average level of physics to each of the game categories summarized in table 3.4, and then in a second pass to associate a numerical *game physics index* with a game by matching attributes of the game that are present in a database to one of the categories in the taxonomy.

This methodology thus makes the following assumptions:

1. The game physics present in a game can be graded over some arbitrary range forming a numerical *game physics index* to be used for further statistical analysis.
2. It is possible to assign a game physics index to a computer game category of a game taxonomy in a meaningful way, thereby extending it.
3. A sufficiently large game database with accurate genre information can be created and mapped to the extended taxonomy.

I will show in the following sections that all of the above assumptions can be satisfied and that this approach thereby provides a valid procedure to analyze game physics in a quantitative way.

3.3.1 Object Dynamics and Spatiality

Section 2.3.4 concluded that current game physics primarily simulates object dynamics. If it can be shown that the root cause for this dominance of object dynamics is the connection between game physics and the way actionable space is created in computer games, the degree of *spatiality* in a game might be correlated directly to the presence of this type of game physics. I believe this to be true and posit that increased spatiality is a good indicator of game

physics in a game.

One can observe that computer games are almost always concerned with the creation and negotiation of space. This preoccupation with the representation of space is so pronounced in computer game design, that it is a driving force for technological advancement (i.e., 3D acceleration in graphics cards) and makes the topic of *space representation* one of the most heavily researched characteristics of computer games (Aaseth 1998). Furthermore, creating such VR and simulating constructed spaces have been key motivators for game design advancements, even in early arcade games. The representation of space in games comes in the form of a virtual architecture which often creates a "supporting front" to enhance the narrative of the game, as it offers concealment and obstacles, exploration and mazes, familiarity as well as surrealism (Adam 2002). Osberg (1997) also demonstrates that a computer game that revolves around any form of game space needs to be spatially managed by the players.

That there exists a link between spatiality and game physics can be illustrated with the game *Lunar Lander*, an arcade game released by Atari in 1979. *Lunar Lander* is at first glance a space-physics simulation, but this popular game of the 1980s attracted many players and transferred the mundane job of "computational physics" from the lab into the realm of entertainment. What was it like to play *Lunar Lander*? A moon surface is represented statically by a horizon drawn as a simple fractal line. Above this highly abstracted "surface," the player controls a rocket vehicle. The lander is subject to the gravitational field of the moon as well as inertial forces, and the object of the game is to safely land under the constraints of a limited fuel supply. The simulated lunar surface is the primary visual element in the game that creates space. To make this simple representation acceptable to the player, it needs to be "modulated" by physical laws, which are made visible through the relative motion of the lander. The game physics simulation

thus creates the actual challenge, and only the direct relationship between the abstract representations of space together with the physics-driven dynamics form the final compelling gameplay. In the years following the arcade era up to today, many games continued to rely on dynamics simulations to turn even the simplest spatial designs into games, as was illustrated through several examples (see Appendix C). One can seldom find any intent by game developers to project actual reality, but often they use object dynamics to make the *designed* game spaces more "playable."

The importance of spatiality in relation to game physics becomes clearer when one investigates problems caused by the wide availability of primarily VR-based games such as the ones in the MMORPG and simulation genres. The current quality and interactivity in the spatial representations of video games creates such a compelling quasi-reality for the players, that they may become a substitute for the real world. While the press has reported on "World of Warcraft" (WoW) addicts that continuously play for days in such spaces (Wright 2006), the real problem has nothing to do with these extreme cases of reality substitution, but with the resulting adoption of VR artifacts or behaviors and their absorption into the player's consciousness and patterns of thought. During play, the player's perspective of speed, force, power and other spatial or material properties changes. Because the simulations of spatiality and game physics are so closely related, extensive exposure to such game spaces impairs players physically when they re-engage with their environment. For example the ability to conduct a vehicle in a safe manner is reduced after playing certain kinds of games, as was described in section 2.4.3, partially due to the player's exposure to the pseudo physics controlling the game space.

It is important to recognize that there are also games where space is not an important factor. Ed Rotberg, the developer of the first VR game *Battlezone*, notes: "In fighting games, for instance, the main concern is the representation

of the physical combat. In many sports games, while negotiating space is a part of the game, the game skills, batting, golfing, running football plays, etc., are at least as important, if not overwhelmingly so, than any negotiation of space." (Rotberg, pers. comm., June 2006) However, physics simulations may still dominate the game mechanics in many of the indicated game genres through the behavior and motion of the game objects or avatars. This is true in particular for 3D games (as was shown in section 2.3.4); and even in games which are not considered spatial challenges, game physics still plays a significant role. For example the sports simulation *NHL 09* (EA Sports, 2009) is marketed with the statement: "An all-new physics-based checking and fighting engine featuring more than 300 new animations brings a higher-level of intensity to the game." (Electronic Arts Inc. 2010)

Sometimes the physics that supports spatiality can be deliberately distorted by introducing movie metaphors. For example, the game *Lunar Lander*, described earlier, introduces a peculiar spatial effect reminiscent of scene-cutting in film. During the game simulation, the game space is subject to a sudden non-physical discontinuity when the perspective instantaneously jumps as the spacecraft approaches the landing field. While this artifact was probably introduced due to the limited hardware of *Lunar Lander*, which prevents the rendering of a smooth scale transition, such spatial disruptions are very common in today's computer games. Many games feature pre-scripted sequences to advance the game's narrative or to enhance the subjective view of the space for the player through cinematic tricks and non-physical motions created by animators, rather than through the physics simulation of the game engine. While live-action, animated or interactive cut scenes are a common design element that deliberately turns off player control and game physics, it cannot be associated with a single game genre. If cut scenes are used in an older game, the presence of game physics might be assumed, since some simulated dynamics must have been present that can be disabled. However there exists a recent trend to avoid cut scenes completely, which was started

with the *Half-Life* game series (Valve, 1998-2004) and is entirely driven by the fidelity of the game engine and its physics simulation capabilities.

In summary, since game physics is the tool that facilitates spatial management through dynamics simulations, the use of game physics automatically increases when games become more spatial. All 3D-based genres such as the popular FPS category necessarily need more game physics than, for example, the spatially simpler Platformer genre. However, many 2D games still exhibit game physics, although generally to a lesser degree. This relationship between spatial game design and the amount of game physics can therefore be used to estimate the game physics index of any game genre, which clearly indicates their reliance on spatiality.[16]

3.3.2 Definition and Accuracy

A definition for a numerical index is needed to perform the statistical analysis of the game design element of "game physics." The numbers 0 to 3 are assigned to a game physics index, as shown in table 3.5.

Although the index is a defined value and therefore introduces no inherent numerical variability, a statistical analysis using this game physics index needs to consider the following sources of error:

- Each index assignment to a category is a manual process which may introduce a systematic error. This will probably not occur frequently, because there is little ambiguity in many category assignments. Also, such errors would apply to the whole dataset and merely shift absolute

[16] One could argue that the reliance on spatiality is a limitation of this approach, as it overemphasize the presence of object dynamic. I think this is acceptable, since object dynamics is the predominant form of standard game physics as was demonstrated in section 2.3.4.

Index	Game Physics	Description
0	None	Games with no game physics (i.e., board games)
1	Simple	Games with very limited game physics (i.e., gravity orientation of a game character as found in 2D Platformer games)
2	Significant	Games with significant game physics (i.e., avatar motions as found in 3D First- or Third-Person Shooter action games)
3	Simulation	Games with physics based simulations (i.e., realistic 3D Simulators for flight, driving or sports)

Table 3.5: Definition of game physics index numbers

averages, but would not affect trends or relative comparisons.

- Similarly, the games within a category may actually exhibit significant variability in their true index number. However, such errors can be considered symmetric about the mean (Gaussian distribution) and therefore would not affect average or trend calculations when a set contains a sufficient number of games.

- Each wrong categorization of a game title would also introduce an error when the incorrect category is mapped to its corresponding index. The number of games considered for averaging in a set (i.e., a particular year) is generally large and consequently the resulting error remains small.

In summary, due to these possible sources of error, any *absolute* measurement of the index values would have a much higher margin of uncertainty associated with it. This needs to be considered when the index is used in a direct way, but the analysis that follows can be used to discuss general trends

and make *relative* comparisons with confidence.[17]

3.3.3 Assignment of Index Values

Using the definitions of table 3.5 and the previous analysis of the relationship between game physics and spatiality, the taxonomy of table 3.4 can be extended to include the *game physics index*. The selection of the index for a game category is based on the assumed sophistication of the spatiality as well as the potential for the presence of a realistic object simulation within the genre. Furthermore, the assignments take the historical context of a genre into account to adjust the index for the effects of technological changes, as discussed in section 3.1.2. Genres that apply to computer games predating certain technological advances such as 3D graphics acceleration will be assigned a lower index (< 2). Similarly, genres such as MMORPGs that became available in parallel to advances in VR technology will be assigned a higher index (> 1). The highest index ($= 3$) is reserved for 3D-based simulation games and the "Artillery" genre, which is specifically recognizable as a physics dynamics simulation. The resulting correspondence of each genre category and subcategory to a game physics index number is shown in table 3.6.

3.3.4 Generation of Database

A comprehensive database of game titles published over the last 40 years can be derived from several online resources. The resulting list of games is organized by release year and includes a category description for each game that can be associated with a game physics index. Three data sources were

[17] For example, it is permissible to make relative statements such as "a generally increasing trend over the last 20 years is observed," but one cannot conclude with certainty that "in 5 years we will have twice as much physics in games than today."

Taxonomy Category	Taxonomy Subcategories	Game Physics Index
Action	Maze, Rhythm	0
	Early Action, 2D Platform, 2.5D Isometric, Fixed Shooter, Slide Shooter, Fighting	1
	3D Platform, First-Person Shooter, Third-Person Shooter, Survival Horror	2
Strategy	Building, Economic	0
	Turn-Based, Real-Time, Fictional Life	1
	Multiplayer-Online	2
	Artillery	3
Adventure	Text Adventure, 2D/Media Adventure	0
	3D Adventure	1
Puzzle	Visual Matching, Hidden Object	0
	Character Control	1
	Construction	2
Educational	Programming	0
	Child	1
	Serious	2
Simulation	Early Space, Early Sports, Early Race	1
	Boat/Submarine	2
	Flight/Space, Vehicle, Sports	3

Table 3.6: Game physics index assignments for all categories of the previous taxonomy (see section 3.2.2 and table 3.4)

used in the presented analysis:

MAME – or *Multi Arcade Machine Emulator* – a software which allows standard PCs to run games from the arcade era. Game data can be extracted by parsing the *mameinfo.xml* file, which is generated by running the MAME executable in a specific mode.

Gamebase – a collection of user-compiled databases containing information about games made for early home computers such as the *C64* or *Amiga*. Game data can be extracted by converting and parsing the various *.mdb* files that make up the *Gamebase* project.

Gamespot – a website offering reviews of commercial games for PCs, game consoles and mobile devices. Game data can be extracted by "scraping" and analyzing the content of many *Gamespot* HTML pages.

The data processing and analysis was performed on an Apple *MacMini* computer running the OSX operating system. The operating system was updated with the relational database *MySQL* as well as various Unix utilities required to execute the data processing scripts.[18] The generation of the *MAME* and *Gamebase* data source files requires also a PC running the Windows operating system in order to execute the PC-based installers.[19]

Processing of MAME Data

The MAME executable is downloaded from `http://mamedev.org/release.html` and run on a PC to obtain the *mameinfo.xml* file using the command line *vmame64.exe -listxml >mameinfo.xml*. The associated *catver.ini* file can be downloaded from `http://www.progettoemma.net/history/catlist.php` and is extracted with the command line *unzip -aa -o catveren.zip catver.ini*. The shell script *process.sh* which in turn uses the perl script *analyze.pl* is executed, to convert these files into a *.csv*-formatted table which is imported into the *mame* database.

[18] Most necessary software can be added to OSX via the *macports* or *fink* projects. *mdbtools* is available as source code at `http://mdbtools.sourceforge.net`.

[19] The raw and processed data as well as the source code of the data processing scripts are made available in Appendix H.

Processing of Gamebase Data

Gamebase installers can be downloaded from several websites.[20] Each obtained executable is run on a PC to install the database files. All files with the extension *.mdb* are collected for further processing. The shell script *process.sh*, which in turn uses the *mdbtools* utility, is executed to convert these files into a *.csv*-formatted table. This table is imported into the *gamebase* database.

Processing of Gamespot Data

A table of platform ID numbers is manually created by analyzing the HTML source code of the page `http://www.gamespot.com/games.html` and stored in the file *platformcodes.txt*. The shell script *scrape.sh*, which in turn uses the Perl script *analyze.pl*, is executed. The script iterates over all platform IDs and page numbers from 1-1000 to generate requests which download pages from the *gamespot.com* website. The game information is extracted from the HTML source code for each page and added to *.csv*-formatted tables. The typical runtime for this process is about one day. Once the scraping process is completed, the shell script *process.sh* is used to import all data files into the *gamespot* database.

Mapping the Physics Index

For each data source, the categories and subcategories (if available) are extracted by running the script *mapping.sh* against each database. The resulting table contained in the file *physicsmapping.txt* must be manually edited to add a physics index number in each category/subcategory row. Once

[20] See `http://www.bu22.com/#databases`, `http://gbst.atomas.com` and `http://robert.hurst-ri.us/files/GameBase20v02.zip`

this manual step is completed, the mapping table is imported back into the database by executing the script *mapping.sh* again. This will also associate each game in the database with the corresponding physics index number via the category label. An excerpt of such a category-to-index mapping list is shown in table 3.7.

Database Category Label	**Taxonomy Category/Subcategory**	**Game Physics Index**
...	...	...
Baseball	Action/3rd Person	2
Baseball Management	Strategy/Economic	0
Baseball Sim	Simulation/Sports	3
Basketball	Action/3rd Person	2
Basketball Management	Strategy/Economic	0
Basketball Sim	Simulation/Sports	3
Beat-'Em-Up	Action/Early Action	1
Biking	Action/3rd Person	2
Billiards	Simulation/Sports	3
Board	Puzzle/Visual Matching	0
Bowling	Simulation/Sports	3
Boxing	Action/3rd Person	2
Business Strategy	Strategy/Economic	0
...	...	...

Table 3.7: Excerpt of the category-to-index mapping used in the statistical analysis of game physics

Table 3.8 summarizes the size of the final dataset created from the three online resources. In total, the database contains 105,000 game titles, includes games published over the last 40 years, and covers 116 game platforms and several hundred game categories. The final analysis is based on 183 game categories each of which contains at least 100 games. All games referenced in the database include the name of the platform, a category/subcategory association, the release year and the mapped game physics index.

Database	Num. of Games	Num. of Categories	Avg. Year
Mame	5,774	152	1990
Gamebase	25,834	387	1989
Gamespot	72,792	142	2001

Table 3.8: Statistics of the game database per source

3.4 Analysis of Game Database

The game database that was created using the procedure described in section 3.3.4 can now be analyzed using Structured Query Language (SQL) queries, which extract and aggregate the game physics index over different dimensions such as platform, genre or year. As expected, the average release year of the games in the more historically oriented *Mame* and *Gamebase* databases are about 10 years older when compared to the average release year of games referenced in the *Gamespot* database.

Figure 3.2 shows the data distribution of all game releases per year across the whole database. One can identify four distinct phases in this graph: (1) From 1975 to 1980, pinball machines where gradually replaced by arcade games, resulting in several hundred game releases by 1981. (2) The peaks in the number of game releases in 1984 and 1989 are due to the popularity of the 8-bit and 16-bit home computers and 1^{st} - and 2^{nd} -generation game consoles released during this time. (3) Similar peaks in 2000, 2003 and 2007 can be attributed to the release of 3^{rd} -, 4^{th} - and 5^{th} -generation game consoles with 3D and HD support. (4) The steep rise after 2008 is due to mobile devices such as the *iPhone* and the corresponding flood of games released via their online "App Stores." One can also clearly see that after 1982, there are over 1000 games released each year.

Figure 3.3 presents the same information again but sorted by the top 20

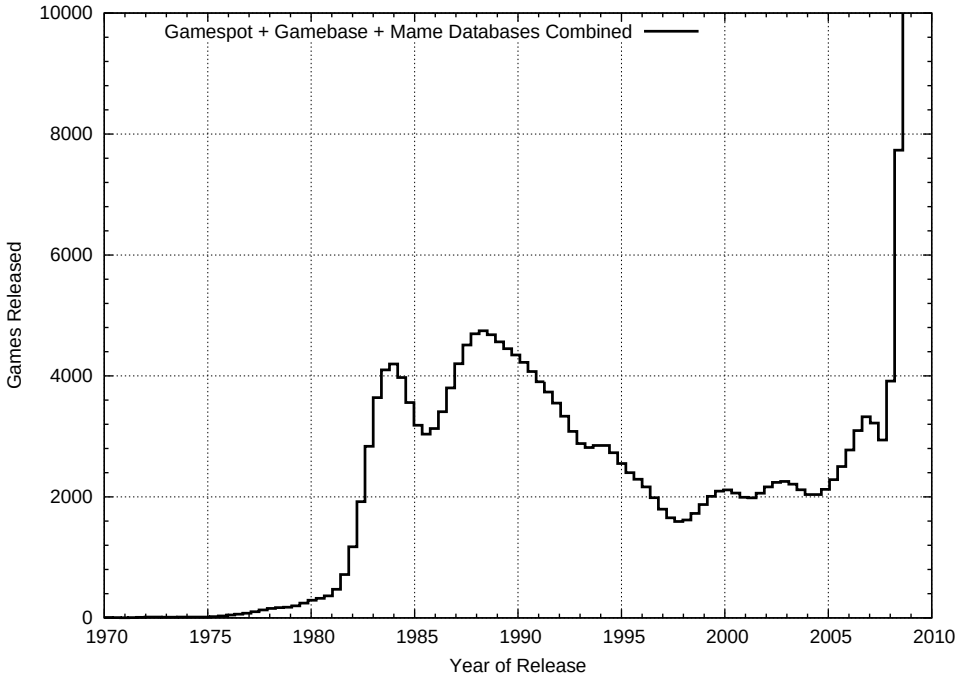


Figure 3.2: Number of released games by release year, 1970-2010 (all databases combined)

game platforms. The figure contains horizontal bars which indicate the first and last game release year for each platform. The three platforms that clearly stand out in terms of the number of games released are the *Commodore 64* or C64 (Commodore International, 1982-1994), the *PC* (various manufacturers, since 1981) and the *iPhone* (Apple, since 2007). The C64's superior sound and graphics performance, low price and good programmability made it the development platform of choice for commercial and hobbyist game developers in the 1990s. The C64 is also credited with starting the "demo scene."[21] The pervasiveness of MSDOS- or Windows-based computers in the

[21]Such "demos" are non-interactive audio-visual presentations that run in real-time on a computer to show off the technical and artistic skills of the programmer. The archive at `http://www.intros.c64.org` for example, contains over 5,800 intros specific to the C64.

marketplace during the last 30 years made the PC the second most popular target platform for game releases. Since PC technology is always at the leading edge of computer hardware with short 6-12-month product cycles, new games will continue to target PC-type devices. Driven by new models of software distribution through "App Stores" and a broadening of the consumer base to non-traditional audiences, the iPhone is the most popular platform for game releases today. The quick rise is partially caused by the release of many existing games which have been ported to this platform in a short period of time, since the hardware capability of the iPhone is comparable to the devices used in the 1990s (i.e., SNES). A comparison of the horizontal release-maxima indicators between commercial consoles and the more open, programmable home computers also shows that consoles have a much shorter time span of active game production.

Figure 3.4 summarizes important game platforms and categories. Of the 20 top release platforms, 7 are programmable devices (C64, PC, Amiga, Atari ST, ZX81/Spectrum, Amstrad CPC, VIC-20), 6 are consoles (PlayStation 2, PlayStation, Wii, Xbox 360, SNES, Xbox), 5 are handhelds (iPhone, BlackBerry, DS, GBA, PSP) and 2 are specialized arcade machines (Arcade Games, MSX). The most popular genres are action, adventure and arcade games. Educational games as well as the edutainment genre of "brain games" are also quite popular development targets.

Figure 3.5 deepens the analysis of the top 20 categories shown previously (figure 3.4) by adding the game physics index of the categories. This chart indicates that 17 out of the 20 most common game genres use *no* (index=0) or *simple* (index=1) game physics. There are two possible reasons for this, which involve preferences of both the game developer as well as the game consumer. On the development side, game physics is more difficult to implement and lengthens the production time and cost. Therefore, more games are made in genres that are easy to implement. This results in a lower physics index

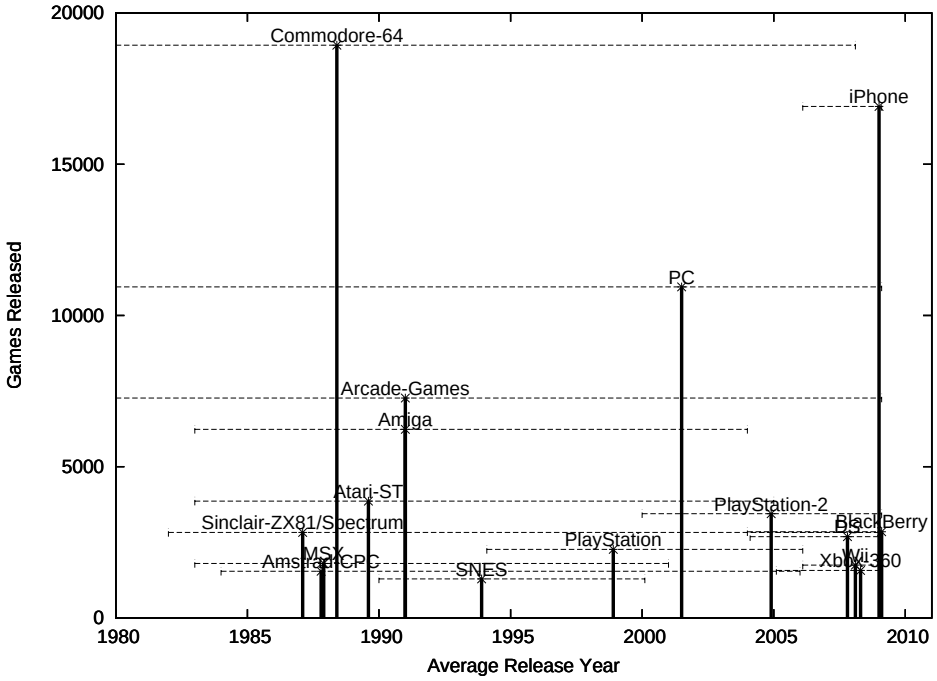
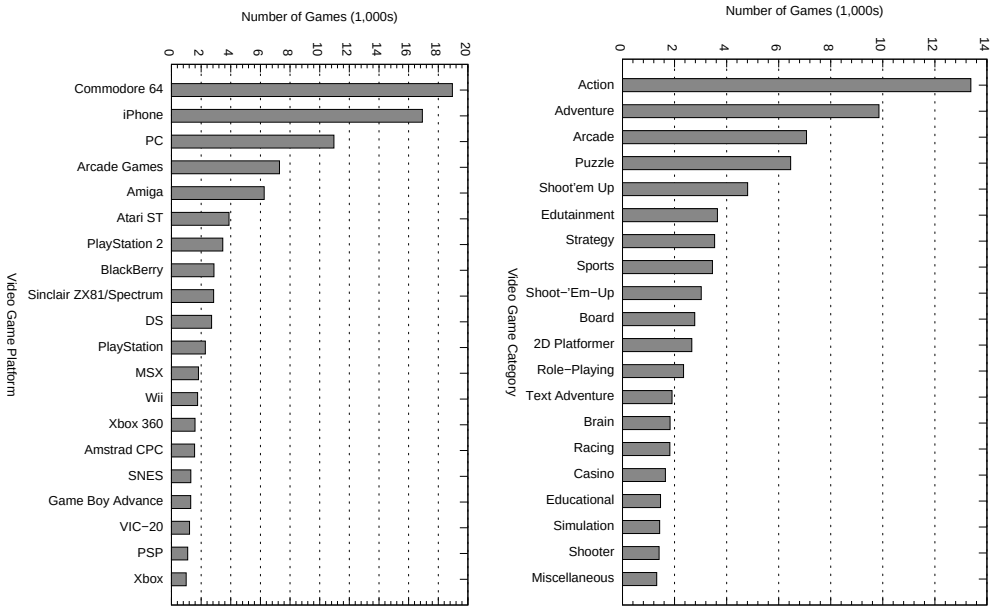


Figure 3.3: Top 20 game platforms over time: average release year vs. number of games released
(horizontal bar indicates first/last game release year)

based on game developer preferences. Advanced game physics is generally only needed for advanced 3D-based VR games. These genres attract mainly "hardcore gamers," whereas the average consumer does not play them due to a lack of the required PC or console hardware. Therefore, a low number of such games are produced due to preferences by the casual game player. However, the racing, sports and simulation genres are present in the top 20 list and do require significant game physics in their implementations.

Figure 3.6 consolidates the game physics index numbers of the whole database into a single graph showing the average physics index per year across all games released. What is immediately apparent is the fact that the



(a) Top 20 Platforms (b) Top 20 Game Categories

Figure 3.4: Important game platforms and categories by number of games released

curve stays well below an index of 2 for the whole time period from 1975 to 2010. In the period from 1980 to 1990, the average index is even lower than 1. This shows that on average, for all released games, the game physics is relatively simple. In other words, for every released simulation game, several other games are released in genres that do not use much game physics.

Figure 3.7 is based on the same data as previously shown in figure 3.6 but adds a *linear regression* to three distinct eras in order to highlight different game physics index trends. (1) During the *arcade era* (1975-1985) we see a downward trend in game physics use as a result of the decline of pinball machines and the rise of digital gaming. While early arcade games such as *Battlezone* and *LunarLander* carried with them some of their scien-

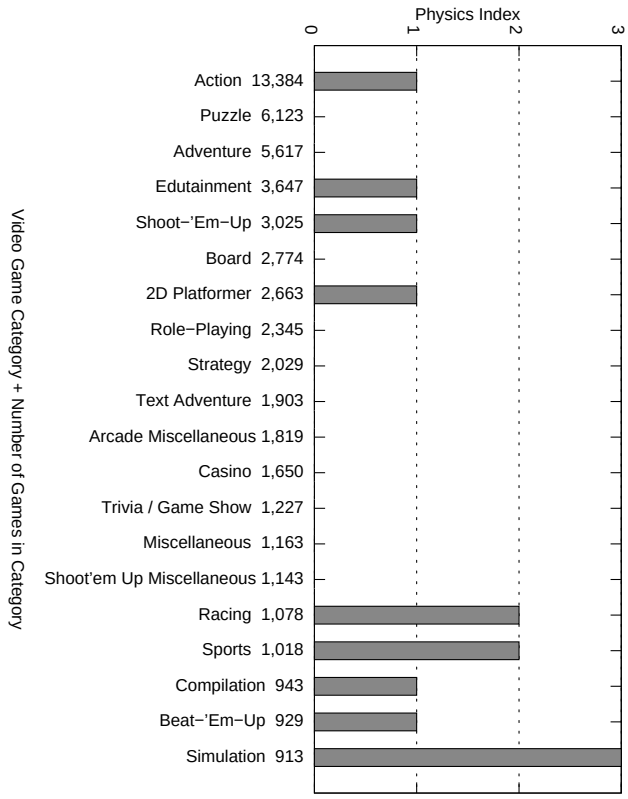


Figure 3.5: Game physics index of the top 20 game categories (0=none, 1=simple, 2=significant, 3=simulation)

tific roots, which is reflected in a more sophisticated game physics early on, arcade games developed later catered to much broader audiences through a variety of genres which did not include any physics simulations. (2) During the *console and PC era* (1985- 2005) one can observe a steady increase in the game physics index, which peaked in 2002, shortly after Microsoft entered the game console market and the *Xbox* 6^{th} -generation console was released. Continuous advances in computer technology and the rise of 3D graphics used in gaming (see section 3.1.2) characterized this period. This change led to a steady increase of game physics use and sophistication and establishes the high baseline for dynamics simulations we see in todays console and PC

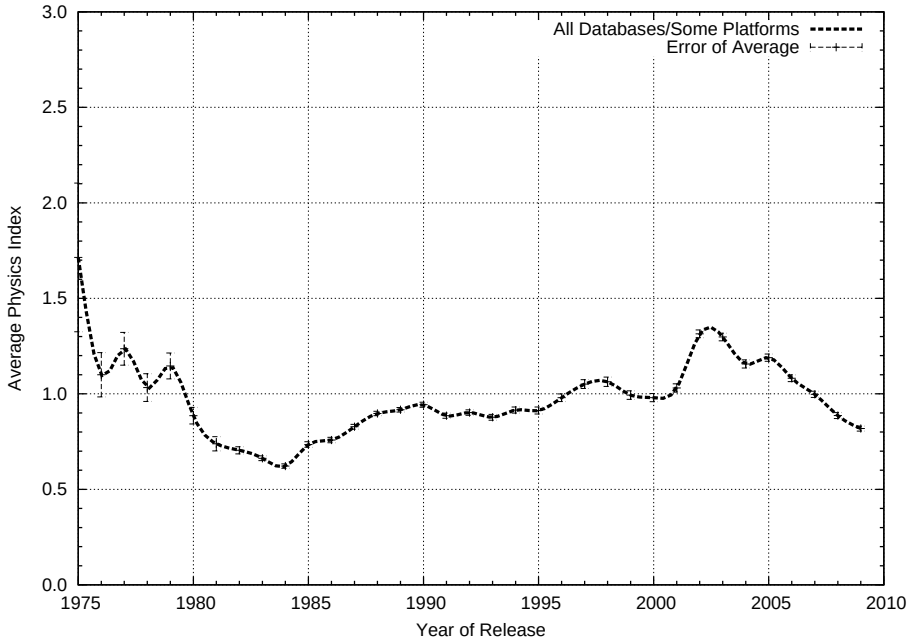


Figure 3.6: Average game physics index per year for all games (0=none, 1=simple, 2=significant, 3=simulation)

games. (3) The proliferation of *mobile devices* in the era after 2005 produces a steep decline in the observed game physics index. This drop is primarily caused by the tremendous broadening of gaming platforms through the availability of capable mobile devices. Because of their technical constraints, these devices are not capable of performing game physics at the levels of sophistication achievable with dedicated game consoles or general-purpose computers.

Figure 3.8(a) shows the top 20 game platforms ordered by the average game physics index of all games released on the platform. The platforms that stand out are *Xbox*, *Nintendo 64*, *GameCube* and *PlayStation 3* with an average game physics index of 1.4 or above. The high game physics index of the *Xbox* is caused by the fact that the device was Microsoft's

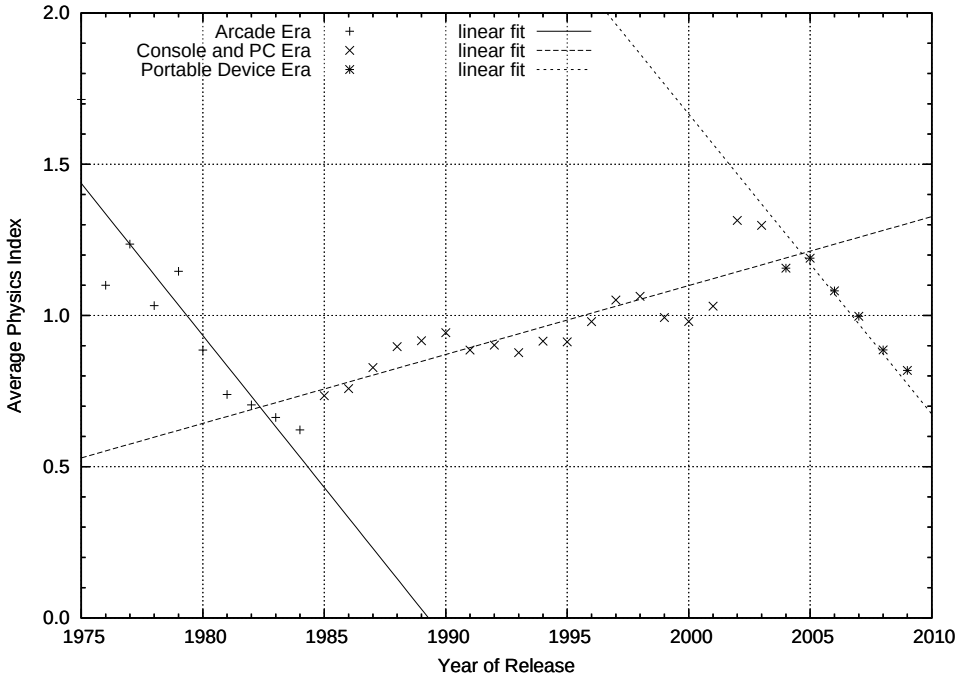
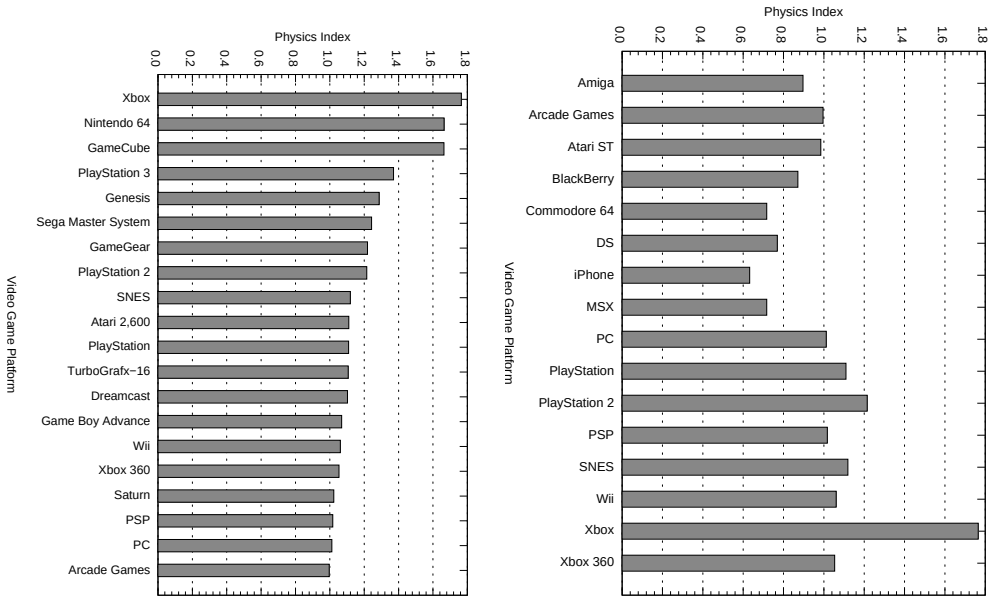


Figure 3.7: Trends of average game physics index over time (0=none, 1=simple, 2=significant, 3=simulation)

attempt to enter the gaming console market. *Xbox* had to compete with Sony's *PlayStation 2*, Sega's *Dreamcast*, and the Nintendo *GameCube*. The game genres that were developed for the *Xbox* used a high level of sophisticated game physics as a marketing tool to attract players. Similarly, games released for the *PlayStation 3* which was introduced into the highly competitive 7^{th} -generation console market, have a high average game physics index to leverage the technological advantage this console had over competing devices. In contrast, the average game physics index of PC and arcade games is only 1, a value that corresponds to the approximate baseline of all games over the last 30 years (see figure 3.6). Figure 3.8(b) alphabetically lists the top 20 game platforms by number of games released, with bars indicating the average game physics index. Again the *Xbox* stands out with a high physics

index for reasons described above. The lowest-scoring *iPhone* is a mobile device, a platform clearly dominated by games that favor genres with little game physics.



(a) Top 20 platforms by index average (b) Top 20 platforms by games released

Figure 3.8: Game physics index of computer game platforms (0=none, 1=simple, 2=significant, 3=simulation)

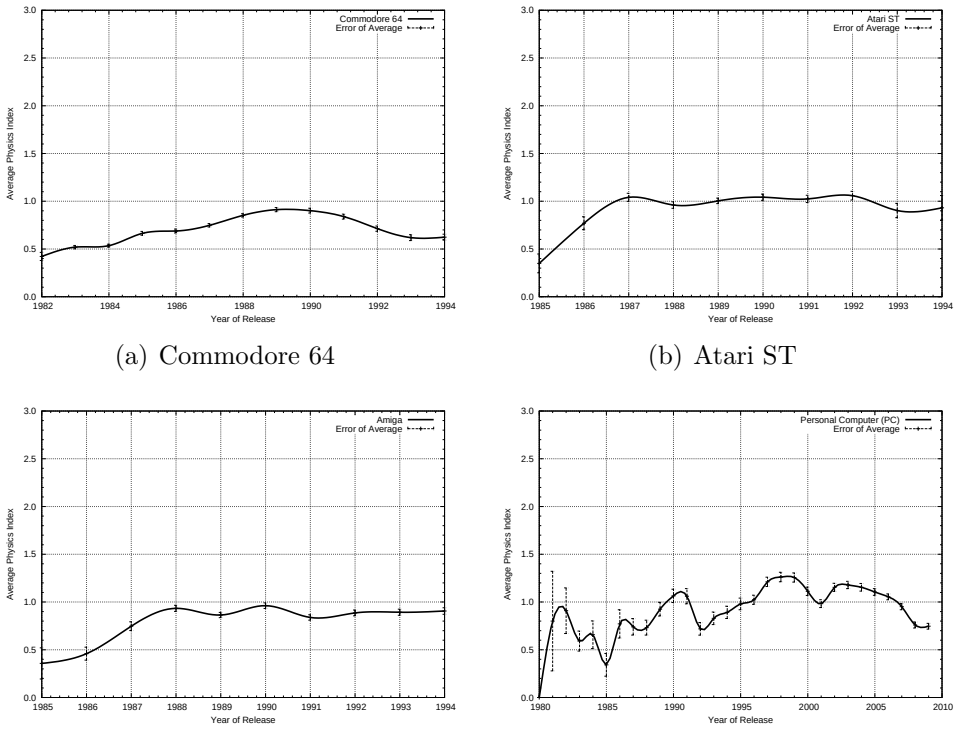
To investigate the influence a game platform has on the evolution of the game physics index over time, the following figures show the index vs. time for important devices in three classes of platforms: non-console game devices such as personal computers, console game devices, and handheld game devices.

Figure 3.9 compares the game physics trends of the *C64* (Commodore, 1982), *Atari ST* (Atari, 1985), *Amiga* (Commodore, 1985) and the *PC*, which are non-console game platforms. For all devices one can identify an initial phase with a rising game physics index followed by a leveling out and later

decline. On the *C64* platform, the index rose for almost 8 years in a row (see figure 3.9(a)) as game developers slowly became more familiar with the technology. In contrast, the next generation *Atari ST* and *Amiga* platforms were mastered by game developers within 2-3 years, as can be seen by a rapid leveling of the index (see figure 3.9(a) and 3.9(a)). The *PC* platform had two rise-phases (see figure 3.9(d)), one from 1985 to 1991 and the second from 1993 to 1999. Both phases correlate well with technological advancements, notably the introduction of the 32-bit Intel i386 processor in 1985 and the more powerful Intel Pentium processor in 1993 as well as the introduction of discrete graphics co-processors by 3Dfx Interactive in 1996. The previously mentioned "demo scene" illustrates the desire of game developers to push a particular game platform hardware to its technological limits to gain competitive advantages.

The console platforms follow a distinctly different pattern when compared to the non-console platforms. Figure 3.10 compares the game physics trends for the *PlayStation 2* (Sony, 2000), *Xbox* (Microsoft, 2001), *PlayStation 3* (Sony, 2006) and *Xbox 360* (Microsoft, 2005) consoles. In each case, the game physics index is highest when the console was launched into the market. The index then gradually drops off over time, which can be attributed to two factors. One is the previously mentioned marketing focus during a console launch, which uses game physics as a tool to highlight the technological capabilities of the new platforms. The second one is the fact that game developers who program and design games for a console do not have to go through a learning phase, because all specifications and capabilities of the device are known in advance and well documented by the manufacturer. Once the capabilities have been explored in some of the first game releases, game developers tend to design games for a broader audience rather than focusing on exploiting the hardware and software capabilities..

Figure 3.11 shows the game physics trend for some popular handheld

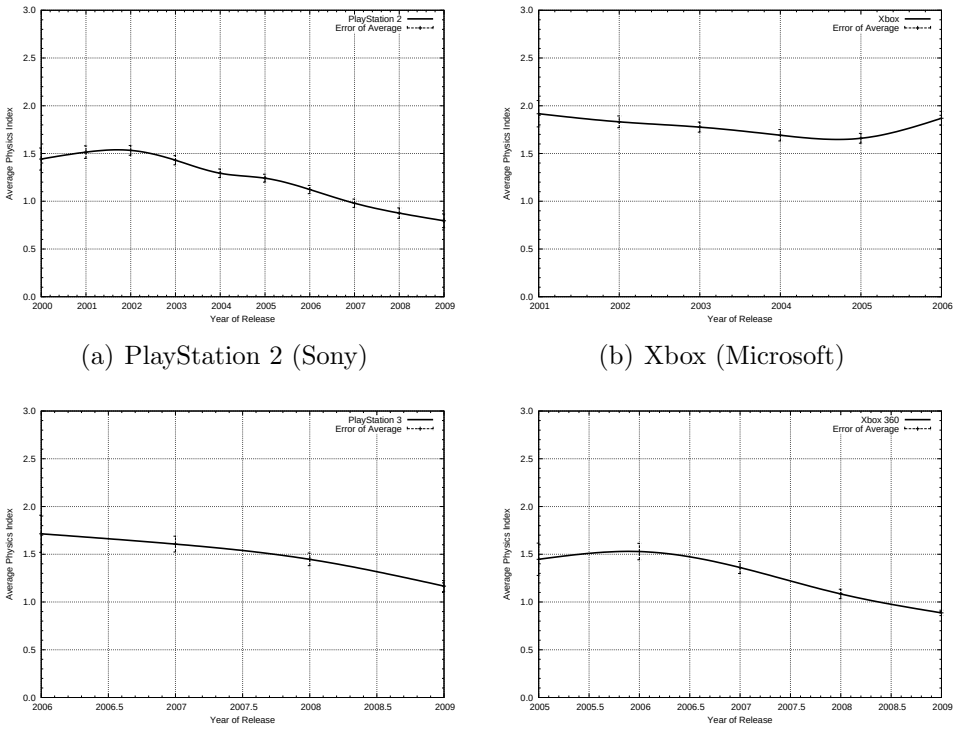


(a) Commodore 64 (b) Atari ST

(c) Amiga (d) Personal Computer

Figure 3.9: Non-console platform game physics trends (0=none, 1=simple, 2=significant, 3=simulation)

gaming devices such as the *Game Boy* (Nintendo, 1989), *Game Boy Advance* (Nintendo, 2001), *DS* (Nintendo, 2004) and *PSP* (Sony, 2004). There is no clear trend across the devices, and the game physics index is generally 1 or less. This level is caused primarily by the technological limitation of these devices. Only the *PSP*, which has some 3D support, follows somewhat the previously observed pattern of console platforms, with a higher initial game physics index followed by a gradual drop over time.



(a) PlayStation 2 (Sony)

(b) Xbox (Microsoft)

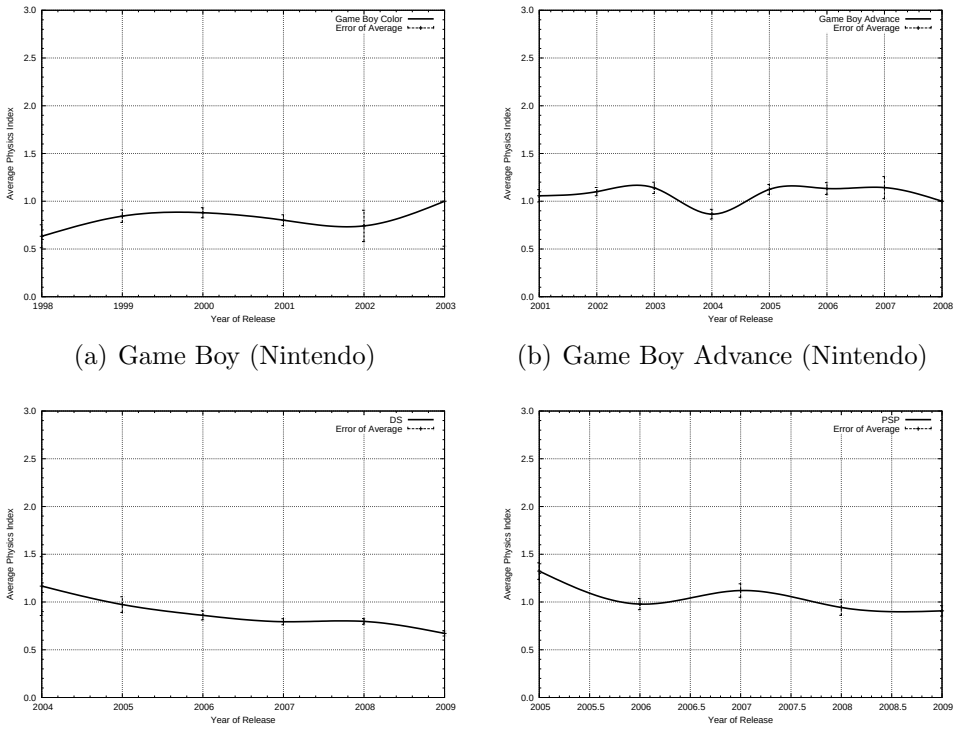
(c) PlayStation 3 (Sony)

(d) Xbox 360 (Microsoft)

Figure 3.10: Console platform game physics trends
(0=none, 1=simple, 2=significant, 3=simulation)

3.5 Chapter Conclusion

It was demonstrated early in the chapter that the computer game industry supplies a huge and growing market with large numbers of games covering a wide variety of game genres. Due to the constant technological advancements, game platforms change rapidly, and this process influences game design significantly, including the use of game physics. Furthermore, releases of new console platforms lead to an increase in the number of published games, because manufacturers try to get customers to upgrade their existing devices.



(a) Game Boy (Nintendo)

(b) Game Boy Advance (Nintendo)

(c) DS (Nintendo)

(d) PSP (Sony)

Figure 3.11: Handheld platform game physics trends
(0=none, 1=simple, 2=significant, 3=simulation)

In order to perform a quantitative analysis of game physics, a methodology was described that allows the assignment of numerical game physics indices to games. Since this process uses the game category as link, a comprehensive taxonomy of game genres was developed and used to map the game physics index. It was observed during the assignment of the game physics index that most of the common game categories do not use game physics in a significant way. However, game physics is an element that is used in 75% of all computer games genres in some form.

For the analysis in this chapter, a database of games was created, marked

up with a game physics index and then analyzed statistically. It was found that the average game physics index across all games and platforms is about 1 (simple game physics), on a scale from 0-3. This game physics index is subject to trends driven by hardware changes. In the usage of game physics, three distinct phases can be identified in the last 40 years. It was found that the use of game physics depends on the type of gaming platform. Non-console platforms tend to use an increased amount of game physics over time, which may be caused by a gradual increase of the game developers' technical familiarity with the platform. Console platforms tend to be launched into the market with a higher level of game physics initially, but the index is then consistently observed to decrease over time. This phenomenon may be caused by an initial marketing-driven focus for game physics when the platform is launched, followed by a broadening of game genres to satisfy the consumers. Mobile and handheld platforms have generally a lower and more constant game physics index due to their limited technical capabilities. A sharp drop in the average game physics index can be attributed to the broad availability of mobile devices after 2005, which created a significant increase of newly published casual games using no physics or very simple game physics.

In summary, from this analysis of the game physics index statistics, I infer that the design goals of game developers who integrate physics are primarily motivated by technological and marketing aspects rather than scientific or aesthetic considerations. These findings – that technological advances may increase but also decrease the amount and quality of game physics in computer games – will be applied in section 5.2.4 to define two additional design principles for *new game physics*. The literature review about theories of play conducted in the the next chapter, continues the search for further mechanisms by which physics could enter computer games in other meaningful ways.

Chapter 4

Theories of Play

4.1 Introduction

In this chapter, I will construct a critical comparison of theories of play through a literature review and show how concepts in the various theories are related to game physics. Why is such a literature review important for new game physics? One of the goals of this dissertation is to construct new game physics elements that provide value to game creators and players alike. Therefore, the primary guiding principle of this review will be to obtain useful structures, "moments," or characteristics which describe certain aspects of computer games in order to define the role of game physics in non-technical terms and point to new mechanisms through which value might be derived from game physics.

It is difficult to provide a comprehensive and at the same time meaningful and concrete definition of play. Numerous scientific disciplines such as biology, philosophy, psychology, pedagogics, cultural sciences, and others have

concerned themselves with the phenomenon of play and have formed definitions constructed from their respective perspectives and special interests. Adams (2006) provides one good starting point to obtain a practical overview of "video game theory," because he compiled important titles into a reading list for game development practitioners. Another source for this comparison are texts used in the study of *ludology*,[1] a term proposed by Frasca, in order to refer to the "discipline that studies game and play activities." (Frasca 1999) Such studies specify a canon for a more theoretical approach to computer game studies. I used both references to choose texts for this review.

Regardless of the desired depth or approach, any study of games throughout human culture from a critical perspective has always considered historical theories of play and the history of games. I have therefore analyzed older texts from Huizinga and Caillois as well as more recent work by Koster, Juul, Galloway and others. My conclusions from this analysis are quite varied. On one hand, as Gee's (2003) analysis on games and learning posits, the content presented in computer games such as the simulations of game physics can easily challenge or reinforce the perspective and worldview of the player. On the other hand, game physics must be put into perspective as only *one* among a wide range of features found in computer games. All these features interrelate with each other and thereby collectively affect the game player.

4.2 Literature Reviews: Historical

4.2.1 Huizinga – Homo Ludens

No review of game theory is complete without mentioning Johan Huizinga's groundbreaking work on play and culture entitled *Homo Ludens* (Huizinga

[1]The term *ludology* is derived from *ludus*, the Latin word for game.

1950). Huizinga originally provided an excellent summary of his book with the article *Nature and Significance of Play as a Cultural Phenomenon*[2] (Beacon Press, 1955). In this summary, Huizinga considers play as essential to all aspects of culture without imposing any morals. He thereby brought a new perspective to the work-oriented cultural climate of his times, which mostly depicted play as a wasteful pastime. "Rather than treating play as part and parcel of cultural value, Huizinga saw it as ultimately transcendent." (Salen & Zimmerman 2006, p. 47)

As Huizinga's arguments noted, all existing hypotheses of play assumed that it served a need or had some biological purpose. He concluded that such definitions deliberately avoided an analysis of the element of "fun" in games, an aspect that he found hard to tackle using logical interpretations. He further questioned the ability of logic, biology or aesthetics to fully explain "play." The importance of play for culture was further underlined by observing that play exists even before culture is established. Therefore, for Huizinga play became "a well defined quality of action which is different from *ordinary* life." (Salen & Zimmerman 2006, p. 99)

Through his work, Huizinga established play-theory as a distinctive concept, and he defined three characteristics of play that are used in many more recent game theories (Salen & Zimmerman 2006, p. 103). These were:

1. "All play is voluntary activity" and only connected with "notions of obligation and duty when it is a recognized cultural function" such as a ceremony.
2. Play is separated from ordinary life through the creation of a new, distinct "sphere of activity." The resulting contrast between play and

[2]The summary appeared as an unmodified reprint in Salen/Zimmerman's anthology (Salen & Zimmerman 2006, pp. 96-120). This summary is used as the main source for the present section.

seriousness constitutes the "power" of games and "play may rise to heights of beauty and sublimity that leaves seriousness far beneath." (Huizinga 1950)

3. Play specifies its distinctness as being "limited in time and place." In other words, this is an extension of the second characteristic and means that games have a specific locality and a defined duration.

All three characteristics are still well reflected in computer games today, since their entertainment goals imply voluntary activity, the technology provides a well-defined sphere of activity, and the gameplay of computer games revolves around the negotiation of spatial and temporal structures. Therefore, others have extended his arguments to serve as a strong indicator, even proof, that computer games play an important role in the creation and definition of most modern cultures. For example, Salen and Zimmerman point out that "to speak of games is to speak in a particular way ... about the cultural models being employed." This perspective indicates that one needs to provide a more refined model for describing physics in games through a language that disambiguates any formal discussion about this aspect of computer games. Such an argument underlines the importance for this dissertation, even though it is conducted in a much narrower subfield of play theory than Huizinga's original text lays out.

Where Huizinga (1950) falls short and was later superseded by other theorists, is his notion of rules, because for him "rules of a game are absolutely binding and allow no doubt." Today, this notion is an antiquated concept, since computer games allow for rapid and fundamental changes of the rules during play, an aspect which opposes the "static" rules in Huizinga's theory. This dynamic approach to rules of course was a development that could not have been foreseen by Huizinga, and probably originates from the fact that, as Juul notes, he "provides only sketchy discussions about actual games as

such." (Juul 2005, p. 10) A productive connection can still be made, though, between simulations of physical laws and Huizinga's notion of absolute rules governing games. Digital computers are in fact the physical embodiment of rules. By their very nature and capabilities, computers allow games to use rule sets that are complex, chaotic, interchangeable and even modifiable by the player during the game. The fact that computer game rules can be very "fluid" means that their game processes may uniquely distinguish computer games from most other games. But this fluidity also shows, that there exists a unique opportunity for the "videogame" medium to deploy more complex rules. My study will therefore investigate the role game physics may play in expanding the diversity and dynamics of game rules that are currently used.

Another potential of Huizinga's (1950) theories in the context of game physics originates from his recognition of the importance of play communities. Huizinga notes that communities automatically form around players of a particular rule set,[3] and that players "surround themselves with secrecy and stress their difference from the common world." (Salen & Zimmerman 2006, p. 107) This actually constitutes a very important similarity between games and physics. It has long been known that, parallel to Huizinga's description of the group-forming power of games, communities also form inside the various fields of physics research when scientists specialize and interact. If one mixes such cultures through game physics, obstacles are encountered when the "community of scientists" needs to interact with the "community of players" or the "community of game developers," causing various communication issues (see section 2.5.3). Similarly, in the computer game communities, it is widely accepted that game rules are constructed purely for entertainment purposes, which differs from how rules are used in the sciences. Therefore, today's use of standard game physics may contribute to the rift that exists between science and the general public, as the game players consciously

[3]rule set = a game

isolate themselves in a certain rule-set – the "pseudo physics" of the game – performing an almost ritualized interaction with the game and thereby blocking any ability for a meaningful interaction with real science. I posit that Huizinga's original research points to a crucial property that new game physics could contain, namely its ability to construct a bridge between such disjointed communities.

One can also connect Huizinga's (1950) ideas with more recent theories proposed for "serious games."[4] Clark Abt defines *serious games* as "games with an explicit and carefully thought-out educational purpose" which are "not intended to be played primarily for amusement." (Abt 2002) It is important to note that the definition of *serious games* by Abt does not exclude the characteristics that Huizinga defines as play. This class of games is in fact an evolution of traditional "educational games." Serious games employ the following factors:

- Competition is minimized and emphasis is placed on the value of the experience (Hark 1997, Nemerow 1996).
- Control over the game flow is stronger (Mungai et al. 2002).
- Competency is emphasized via feedback mechanisms (Mungai et al.).

The theorist Rodriges (2006) further proposes that Huizinga's work includes claims that make it very compatible with the goals of *serious games*. He concludes that for Huizinga "the activity of playing reflects neither a mindless biological mechanism nor a logical inference; it is supra-logical[5] and yet not subject to blind causality." Because of this, "playing emerges as a profoundly serious activity." Rodriges locates two specific play features that are key elements in serious games. These are Huizinga's *magic circle* which

[4]Because of their educational purpose, serious game studies are relevant to game physics, if the aim of a game is to teach physics.

[5]From latin *supra*, above

corresponds to the topical communities that form around serious games (as discussed above) and the exploratory nature of game-based learning, which according to him highlight the ludic aspects of science and other serious academic subjects. Both of these findings support some aims proposed earlier in this dissertation that are specific to game physics: engaging communities in specific game physics implementations are key to their success, and "playful" science has a legitimate potential.

4.2.2 Scheuerl – The Phenomenon of Games

A highly generalized definition of play, yet one still having a large amount of expressiveness, could be derived from a theory that focuses on the phenomenology of play and is motivated by a psychological analysis of the subject. In 1954, the German professor of education Hans Scheuerl (1954) presented his relatively unknown theory in *Das Spiel*[6], about the phenomenology of games. He analyzed several definitions of games and extracted common attributes from them. He also included additional characteristics of play beyond Huizinga's (1950) analysis and thus his theory may yield further insights into how game physics could function in a computer game.

Scheuerl (1954) arrived at six characteristics or "Moments" which can be identified in computer games; some even have a strong relationship to game physics, as I will show.

The Moment of Liberty From the point of view of the player, games are free of direct purpose; while work, for example, has the purpose of making a product, games only exist for their own purpose. Furthermore, the experience of the moment of liberty is only available to the player, a fact that makes this moment one of the core incentives to play the

[6] eng. *the game*

game in the first place.

The Moment of Infinity The internal process of play attempts to repeat itself ad infinitum. Every game has an end, but it is immediately followed by the opportunity for revenge (i.e., in *Bridge* or *Skat*), restart (i.e., add another coin into the arcade game) or a new game cycle (i.e., in *Lotto*). It is this moment that gives games a great potential for addiction.

The Moment of Semblance A game has always some fundamental differences from any other process in reality, even if it is trying to "pretend" to reflect reality. Scheuerl sees this moment in a very positive non-deceiving way. For example, this moment allows a player to attain a game state repeatedly, offers all the possibilities of play and includes the ability of games to create their own realities.

The Moment of Ambivalence Game processes must be open in their result and include some randomness or unpredictability.

The Moment of Relative Closeness All games must be constrained by an underlying system of rules – they become closed – while maintaining relative freedom within the rules.

The Moment of Presence The player creates a new game time and the measurable, material time is delegated to a background role during play. The player's presence in play is an "experience of the instant." This feeling can be linked to biochemical markers of happiness, causing players to lose their sense of time.

Computers can master the *Moment of Ambivalence* very well, because ambivalence can be easily created from the raw computational power: the creation of an infinite number of variations can be instantiated through random

number algorithms. Game physics can be instrumental in creating ambivalence because it often describes non-linear or coupled systems, which exhibit a large *variation-space* and thereby add additional levels of unpredictability to gameplay. However, the focus in contemporary game physics is seldom one of "richness," and there are many more possibilities that physical systems can provide which have yet to be used in computer games. An even more important point requires further investigation: digital computers generally employ Pseudo Random Number Generators (PRNGs), which are simulations of randomness itself. This fact may have significant implications for this particular moment within computer games and warrants further practical exploration later in this dissertation (see sections 5.6.2 and 5.9.1).

Within the current trend in VR-oriented 3D worlds, there is a distinct preoccupation with the *Moment of Semblance*. This focus has a long tradition in game development, as early game platforms with their limited capabilities made the creation of any form of "semblance" very hard work indeed. Consequently, the game industry is shaped by a preoccupation with VR, as every new generation of game platform in the last few decades has focused on creating a better audiovisual immersive experience for the player. In computer games, game physics is used in a similar, purely utilitarian way. However, the result rarely allows the player to experiment with the realities created by it. Simulations generally lack the ability for adjustments and are often static metaphors for the reality they attempt to represent. Therefore, new game physics should seek to enrich games by providing additional dimensions for the *Moment of Semblance* and allowing some player control over them.

A computer game is also predestined to offer unlimited amounts of *Moments of Infinity* simply because repetition is what a computer does best. Unfortunately, repetitive gameplay is also a prime cause for the many problems associated with computer games, as players become addicted to the endlessly repeating game worlds where "game-death" is followed by a "rebirth"

from the last "save point" just seconds later. Many computer games facilitate such repetition, which has a significant negative side effect, in that it makes games an instrument of "rote learning." Such old-fashioned teaching techniques emphasize memorization and are strongly discouraged by many new curriculum standards, especially in the communities of science and physics (Quirk 2002). Appropriate game physics could play a significant role in providing new game elements that counteract repetition and the associated "rote learning" offered by this *Moment*. Thus, while new game physics elements may need to embrace rules that create infinite possibilities, they would also need to avoid repetition and encourage learning through discovery at one's own pace and on one's own terms.

4.2.3 Caillois – Les Jeux et les Hommes

In his well-known book *Man, Play and Games* French intellectual Roger Caillois (1962) expands on Huizinga's philosophies in several ways that are useful in the context of this study. Caillois agrees with the key point posited by Huizinga (1950), who suggested that culture is derived from play. Caillois states that play "creates and sustains the spirit of inquiry" and provides the means for "man to check the monotony, determinism and brutality of nature." (Caillois 1962, p. 58) However Caillois' ultimate intent is to investigate the social consequences of play. Because I hope to investigate the social impact of game physics on players, this thesis can possibly help to expand Caillois's theory.

Caillois certainly defines the activity of play in a more flexible way than Huizinga, by adding uncertainty, non-productiveness, and make-believe to the already noted characteristics of freedom, separation and rules. He then continues to specify a well-known classification of games into four concepts:

agon, *alea*, *mimicry* and *ilinx*.[7] These classifications are treated as inherently fuzzy definitions, but he proceeds to connect and contrast them as shown below (figure 4.1).

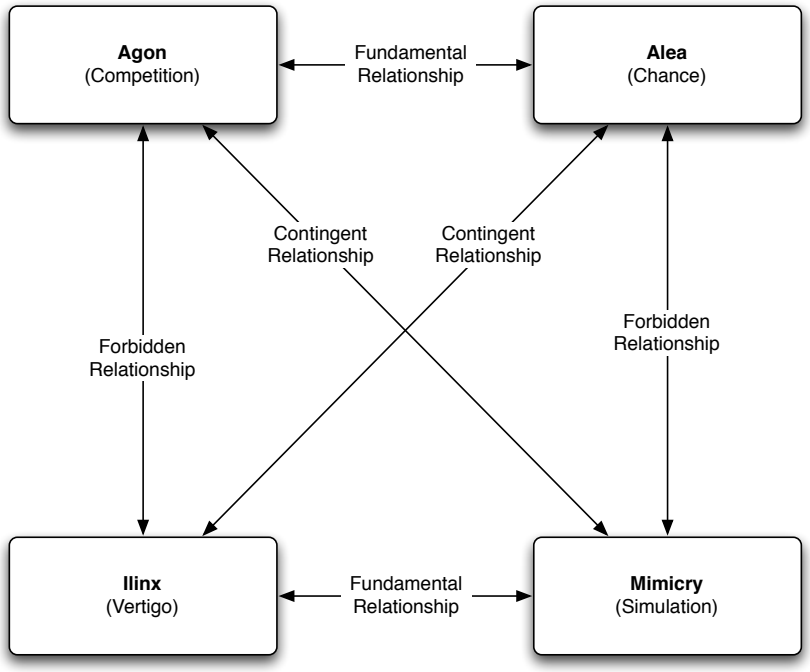


Figure 4.1: Adapted from *Man, Play and Games: An Expanded Theory of Games*, chapter IV (Caillois 1962)

Caillois (1962) did make a few assumptions which show that his definitions are now out of date, especially when attempting to apply them to current computer game scenarios. In his scheme, Caillois excluded the possibility of combining chance with simulation (*alea* and *mimicry*) when he claimed

[7] In Greek drama, *agon* refers to the formal convention for the struggle between the characters in order to create action. *Alea* is borrowed from the Latin phrase "alea jacta est", meaning "The die has been cast", commonly associated with J. Ceasar (49 BC). *Mimicry* is derived from the Greek term mimetikos, "imitative," in turn from mimetos, the verbal adjective of mimeisthai, "to imitate." *Ilinx* is the Greek word for "whirlpool", which is taken to mean "vertigo" or "the pursuit of vertigo" in this context.

that "games are not ruled *and* make-believe. Rather, they are ruled *or* make-believe." (Caillois 1962, p. 9) Today, any common computer game genre that uses 3D game worlds demonstrates that this separation hardly exists. On one hand, fixed maps and sophisticated game physics are used to govern bodies, objects and their interactions in the 3D world by providing strict rules. On the other hand, the interactive gameplay offers unlimited amounts of completely random possibilities and configurations in the play-space.[8] Therefore, computer games tend to break these structures posited by Caillois. In fact, all popular genres of computer games including action games are almost certain to make use of the element of chance (Juul 2005, p. 13). I surmise that the computer medium has completely broken down Caillois' forbidden relationship between *alea* and *mimicry*. As Juul confirms, "It seems more reasonable to describe chance as one single example of a multitude of game design principles." (Juul 2005, p. 10) This is exactly the approach that new game physics designers should take regarding *alea*, as randomness and complexity can become a common game element even in situations where they are normally uncommon.[9]

The analysis of Caillois (1962) raises a few additional points which extend this research into game physics. For Caillois there exists an equivalence of the physical and the mental competitive elements of games – or as he names them, their *agon*. According to Caillois, the desire to win and the need for practice is presupposed for competitive games, while games of chance are categorized as non-competitive because they often negate the "work, patience, experience and qualifications" of the player. This is a common belief, but I posit that these motivations are similar and share a fundamental relationship. Caillois himself states that both competition and chance provide "conditions of pure equality denied [to] them in real life." (Caillois 1962, pp. 17-19)

[8] According to Caillois, this would constitute the incompatible characteristics of *alea*.

[9] Sections 5.6.2, 5.8.1 and 5.9.1 will explore game elements using physical randomness and complexity in unusual play situations.

Therefore, the reason for the success of many computer games must lie in a unification of all players in competitive *and* non-competitive situations, which are "not part of real life." The success of such a union would have an important implication for game physics. If the application of physics in a game constitutes an element of reality in a non-competitive situation, or if chance is derived from physical reality, one could then question if game physics still supports the benefits of Caillois' *agon* in the game. This dissertation will investigate the question: "Does adding real physics or physical randomness to a game destroy the unifying properties in a game?" Experiments with this approach in a game prototype can be found in chapter 6, but it is also important to note that *mental agon* could be a very important part of game physics, since physics is actually a cognitive exercise. Perhaps new game physics elements could be designed as an application of the scientific method in competitive game situations involving game physics.

Similarly, the pursuit of vertigo, or *ilinx* as Caillois (1962) calls it, is a physical as well as a mental or cognitive activity. Caillois keenly observes that "the industrial revolution had to take place before vertigo could really become a kind of game." (Caillois 1962, p. 78) One could argue that the ongoing "digital revolution"[10] of the information age is the foundation for a new class of games that can provide the player with a unique form of *mental vertigo*. Today, many of the highly competitive multi-player computer games have presentations and aesthetic forms which are ultimately designed to provide a significant amount of mental vertigo on top of the their agon-based play structures. New game physics elements may be able to play a much more significant role in creating such mental vertigo for entertainment purposes,

[10]The term *digital revolution*, also called information revolution, is a theoretical construct through which trends in current society related to computing can be conceptualized. The use of the word "revolution" relates to the previously used terms *agricultural revolution* and *industrial revolution*. and alludes to a global economy's shift in focus away from the production of physical goods (as exemplified by the industrial age) and toward the manipulation of digital information.

although it is not clear from the quite dated discussions by Caillois how this may be achieved.

The element of *mimicry* as described by Caillois (1962) is a unique rule of the game in which "the spectator must lend himself to the illusion without first challenging the decor, mask, or artifice. ... For a given time he is asked to believe in a reality more real than reality itself." (Caillois 1962, p. 22) Recognizing the power of illusion in games, Caillois foresaw the basic mechanics of most computer based game worlds that players "inhabit" today as VR. An important connection about the presentation of science to an audience of scientists can be derived from this statement. For Caillois a combination of *mimicry* and *agon* is "immediately destructive" but also on some level "truly creative." He also mentions that the player needs to be *asked to believe* in order to be able to compete. Hence, I can conclude that one must use the seductiveness of *mimicry* to overcome the challenges posed by mental *agon*. In the game physics context, new game physics must therefore attempt to embed the physics as believable VR artifacts into the game so that *mimicry* can be created. Only then can one use the contingent relationship between the two characteristics to help the player in his/her "identification with the champion" (for example another scientist). Therefore such a combination "in itself constitutes mimicry" (Caillois 1962, pp. 22-23) and provides the additional enjoyment from a game that is based on mental challenges, a factor which would normally be rejected by the players. I believe that in order to construct effective game physics elements that combine mental challenges with mimicry, the psychology of play needs to also be considered in more depth.

4.2.4 Heckhausen – The Psychology of Play

Heinz Heckhausen (1973, 1989), a German psychologist who was active in Gestalt Psychology, reviewed the motivation behind games in a book entitled *Entwurf einer Psychologie des Spielens*[11] (1973). In it, he reveals many elements that could serve to broaden the spectrum of game-theoretical approaches related to game physics.

In psychology, many researchers always saw the explanation of "play" as a challenge because of the general lack of observable purpose in most games. Heckhausen recognizes the limitations of a phenomenological approach in defining play as a simple summation of characteristics. While features described by Buytendijk (1933), Huizinga (1938) and Ruessel (1953) are all convergent, they are unable to provide an explanation that goes beyond treating play as a basic phenomenon of life itself. To overcome this shortcoming, Heckhausen prefers a genotypical approach to the common phenotypical analysis of games,[12] which focuses on the comparison of play with other behavioral phenomena.

His analysis adopts the following 5 basic features of play:

1. the freedom from serving a specific purpose
2. the cycle of activity, alternating between tension and resolution
3. the active challenge of only a part of reality
4. the undifferentiated structure of goals and the immediacy of time for the player

[11] eng. *Outline for a Psychology of Play*

[12] Genotype and phenotype are terms which are normally used in Biology to describe an organism, but other fields of science have also adopted them. A phenotype describes any *observed quality* of an organism, such as its morphology, development, or behavior, as opposed to its genotype, which describes the inherited instructions or *genetic constitution* it carries, which may or may not be expressed.

5. the quasi-reality created by the game

While Heckhausen's *freedom of play* is a feature of games commonly noted by most other theorists, he posits that this feature is shared with many other non-game behaviors such as reflective recreation, puzzle solving, research, philosophizing, artistic design, various forms of entertainment, and the engagement of travel. Furthermore he explicitly states that "research" within the practice of physics could be treated as such an activity – a form of game – where the scientist exercises his freedom through his work. According to Heckhausen, if specific goals are observed in play, the *freedom of purpose* in games implies that goals become rules. Therefore any restrictions that definite goals would impose on the "freedom" of the player can be resolved and the motivation would be kept "free."[13] While researchers may question if a computer game can elevate the conduct of scientific research into a "free play" scenario, Heckhausen's analysis shows that new game physics elements could certainly play a role in motivating physicists to participate in gaming by creating a game-space that may be free of traditional research purposes, but still retains the rules of the underlying physics in the game physics simulation. He even lists general *modes* that turn an "activity for its own ends" into a game, which could be applied to the implementation of new game physics elements. These are as follows:

- The presence of an agent with which the player interacts; there is always "something" playing with the participant of a game.
- A simple goal structure with an immediate perspective on the objectives to facilitate a short time-period is required to enable effective activation cycles.

[13] According to Heckhausen, such a result was shown experimentally through multiple examples in an analysis performed by Duncker (Duncker 1940/41, "*On pleasure, emotion, and striving*", opus posthumum, p. 403-404)

- The provision of a "quasi-reality," which separates, excludes and heightens space and time of the reality. However, the player is still aware of the illusion, and adults may require explicit rules to maintain this separation.

Heckhausen (1973) notes the importance of activation cycles that can also be observed in many other behaviors besides play. Since games tend to show more repetition, he uses the word "cycle." The *cycle* of a game, a particular timing of tension buildup and release, was first described by Berlyne (1960) as "arousal jag," and Heckhausen extends this analysis. There are two key features to such cycles. First, he recognizes that our emotional experiences tend to swing around a mean, where too much or too little stimulation can be perceived as highly undesirable or can even inhibit our cognitive functions. The second feature is related to the level of tension. In anticipation of the forthcoming resolution, a player will often tolerate much more tension as "fun" that would otherwise be considered pleasurable. Heckhausen's psychological insight into the function of games is very important, if one wishes to apply physics to games. In particular, new game physics should provide additional means to create the aforementioned *cycles*. This may be difficult to achieve, since game developers must become aware of all available activity cycles in computer games in order to consider adding game-physics-driven ones in their designs.

Therefore, this study will investigate Heckhausen's (1973) analysis of the constellations of activity cycles that seem especially successful with game players in order to inform game physics design. He lists 4 "discrepancies" which are the sources for the cyclical stimulation-potentials in games, and each category produces some well-known responses from players:

1. The discrepancy between the current and the previous experience and

sensory input. This is visible in the inherent curiosity of children - one of life's "necessities" for Piaget (1936). It also forms the foundation for whole industries to satisfy adults by providing them with a constant stream of *new* experiences.

2. The discrepancy between the current experience and the anticipated experience derived from all past experiences. The *activating powers* of any discrepancy are inherently short-lived, because the player quickly begins to understand and compensate for it through a learning process.
3. The discrepancy between different parts of the perceptive-field leading to increased attention of these fields. This discrepancy is the origin for the motivation to solve problems and to engage in "free" thinking and non-goal-oriented research.
4. The discrepancy between different expectations and tendencies, leading to stimulation through the perception of thrill, risk, and danger as well as unresolved conflicts or defeat.

When stimulated by such discrepancies, players often experience positive emotive reactions. These sensations result from medium-level discrepancies which are neither too weak nor too strong; shifts and fixations in the cognitive focus; sensory and locomotive reactions for orientation purposes; exploratory behaviors and trial-and-error actions; and finally, balancing interactions in the brain itself. An awareness of the above stimulation cycles and their effects can be used to make existing and new game physics elements more effective. While a detailed psychological analysis of game elements is beyond the scope of this dissertation, future research would probably benefit from a comparison of these theoretical findings with actual statements from game players about game physics, such as the ones collected during the survey discussed in section 2.5.2, in order to evaluate game physics elements for their activation potential.[14]

[14]See Appendix F for the actual player statements.

Psychologists generally agree, that games are an important element in the development of our sense of reality and the cognition of substantialities. When game physics is targeted to adult audiences, another important psychological implication can be derived from Heckhausen's (1973)analysis. Games may be split into two broad categories depending on their ability to increase or decrease the emotional activation level. An increase in the level of stimulation can activate both positive (e.g., interest) and negative (e.g., startle, fear) emotions, whereas a decrease in the level of stimulation tends to only activate positive emotions such as joy. This principle is applied, for example, in games that decrease the emotional activation level in order to improve the behavior of children after traumatic events or those in the middle of psychotherapeutic recovery. But this type of game use is rare, and almost all computer games are designed to increase the emotional activation level. Adults however often perceive their environment as familiar and rationalize the same unknown, interesting, dangerous and alluring elements that drive these activation potentials of play in children. Consequently, adults generally perceive games as an activity with little value for knowledge acquisition. This perception creates an enormous barrier that makes the interaction between physicists and game developers or players very challenging. The fact that the "adult scientist" outright rejects games for learning physics was apparent from some of the responses found in the physicists' survey (section 2.5.3). In order to get adults to interact with games and game physics, one must consider the *activation potential* that a particular type of game physics provides for an adult audience. Thus, for computer games or interactive art installations to become acceptable for a trained scientist, the "unknown" must be clearly recognizable and new game physics elements must be designed with appropriate background information for these users.

4.3 Literature Reviews: Current

4.3.1 Juul – On Rules and Worlds

The comprehensive computer game analysis by Jesper Juul entitled *"Half-real"* (2005) posits that computer games generally combine real rules and fictional worlds at a scale that makes them distinct from all previous game types.[15] Through a review of game theorists, he shows that one of the most common assumptions about games is that they are considered to be based on rules. Similar to other game theorists discussed in this chapter, he presents a model of "What a Game Is." Juul's definition consists of a set of six characteristics, which are present in anything one would call a game and which demarcate games from non-games (see figure 4.2). Juul suggests that "a game is a rule-based formal system with a variable and quantifiable outcome, where outcomes are assigned different values, the player exerts effort in order to influence the outcome, the player feels attached to the outcome, and the consequences of the activity are optional and negotiable." (Koster & Wright 2004, pp. 12-14)

Juul verifies that computer games consistently add fictional worlds or "a fixed set of signs to aid the player into imagining things." (Juul 2005, p. 2) He notes that computer games are often structured differently than many traditional games in that they provide challenges along a narrative progression rather than relying on their emergence from a small number of rules.[16] This is deemed a direct result of the effort to combine storytelling elements

[15] This is similar to Caillois' finding on *mimicry* discussed in section 4.2.3.

[16] The game of chess is a prime example of the emergence of complex challenges from a very limited set of rules. The smallest computer implementation of chess ran on a ZX81 computer with only 1024 bytes of memory (Horne 1983). This simple program provided essentially the full implementation of chess, although it probably lacked competitive strength due to the limited hardware.

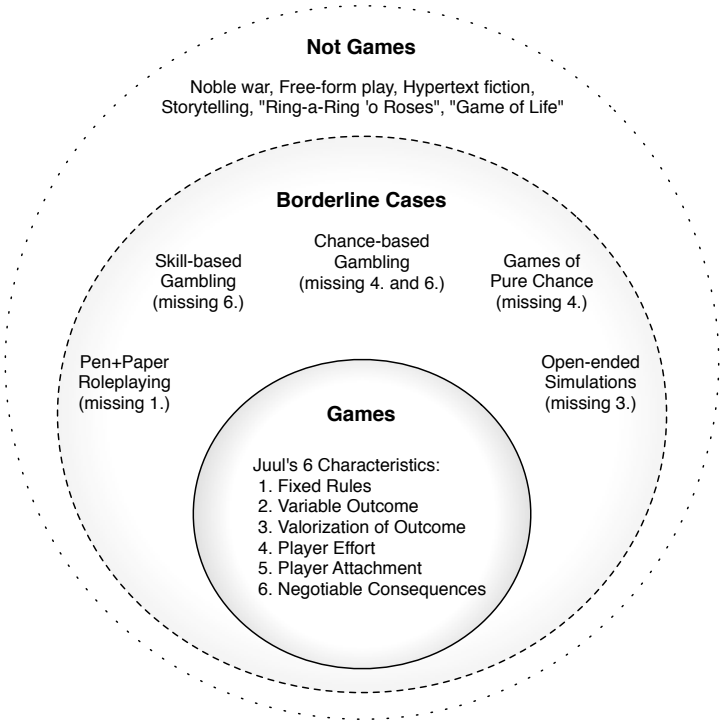


Figure 4.2: Juul's Borders of the Classic Game Model; adapted from Juul (2005, p. 44)

into a computer game and is also an indication of the desires of game developers themselves to gain more control over the structure of the game. According to Juul, the fictional worlds which are considered to be a common design component in computer games are embedded "ingredients" and often "contradictory and incoherent." However, this observation does not seem to impact on the player's relationship with the game, because "the player may not experience this as such, since the rules of the game can provide a sense of direction even when the fictional world has little credibility." (Juul 2005, p. 6) One could conclude that, for Juul, any fictional game world is in a subordinate role to the ruleset of the game, at least from the player's perspective. In relation to game physics, this analysis seems to fit very well

with the status quo in current computer games where non-credible pseudo physics are the accepted norm. One shortcoming of this definition of games focused on rules, however, is that it tends to leave out the possibility of *free play* through computer games. For example in free-play situations of traditional game circles by children, the rules are very rarely as fixed as Juul's definition would suggest.

I agree that the proposed relationships between rules and fictions are not arbitrary but are always "based on a background of some existing antagonism" (Juul 2005, p. 15), with which the players often deal in a satirical or allegorical way. This attitude or process is described by Juul as a form or "transmedial storytelling" which builds a bridge between game rules and game fiction. Culturally, however, he places this form of storytelling ecology at a "toy" level, lower than the narratives generally found in movies. In particular, he places complex interactions between humans, such as friendship, love, deceit and even the rules of sports, into the "Borderline Cases" category (see figure 4.2), simply because they are "hard to implement in rules!" (Juul 2005, p. 20) Juul also finds that it is very difficult to realistically implement the physics of something (Juul 2005, p. 49). With this argument, he has actually determined the two primary causes that lead to pseudo physics in games in the first place: (a) a lack of background knowledge and (b) a lack of effort to implement real physics. As this dissertation suggests, transdisciplinary game design teams involving scientists may be able to overcome cause (a), whereas the value proposition of new game physics may provide the incentive to resolve cause (b).

On the question of how fun is derived from *fixed* rules, Juul (2005) asks a very rhetorical question: "Why be limited, when we can be free?" He posits that the primary reason for this limitation is based on the fact that "games [need to] provide context for actions." (Juul 2005, p. 18) This statement is very relevant to the discussion of physics in current games, because standard

game physics was found to be generally confined to just dynamics simulations (see section 2.3.4). If one were to adopt Juul's reasoning, game physics that is derived from broader subfields of physics would not be able to create any context for the players, due to their limited knowledge of physics or scientific methods. Juul does consider *simple* physics as a possible game rule (Juul 2005, p. 50, Table 2.4), but he does not consider physics simulations and physics-based Augmented Reality (AR) as a possible rule set, because "rules are designed to be easy to learn, to work without any ingenuity from the player." (Juul 2005, p. 55) I propose that new game physics should *not* adopt Juul's previous argument. Not only would it be very counterproductive, but it would actually prevent the advancement of game physics, which is the goal of this dissertation

However, Juul's (2005) discussion on rules makes an important point relevant for this game physics analysis, because it extends Caillois' (1962) *alea*[17] and Scheuerl's (1954) *Moment of Ambivalence*[18] with concepts from digital computing. The assumption Juul posits about rules and the construction of computer games is that rules constitute a generalized state machine which creates "a branching game tree of possibilities from moment to moment during the play of the game." (Juul 2005, p. 56) While this view is applicable to games like chess, which have essentially been solved by a computer using the analysis of the game state tree (Feng-Hsiung 2002), Juul is trying to apply this as a simplification about game rules in general. For him computer game rules are always entirely finite, digital, and quantized. This means games are treated as Finite-State Machines (FSMs), and this property is used to derive the primary purposes of rules and demarcate them as elements within games. Rules often limit the player's actions, setup potential actions, specify limitations and affordances, give the game structure, and prevent the players from reaching the game's goal too quickly. A lack of such rules constitutes

[17]See section 4.2.3.
[18]See section 4.2.2.

a non-game for Juul and he cites John Conway's *Game of Life*[19] not only as "an example of emergent properties of some simple rules" but also as a typical *non*-game (Juul 2005, p. 78). Could physics proof him wrong on this point? Juul does acknowledge that computer games such as sports games "require that the laws of physics be explicitly implemented in the programming in the same level as the explicit rules of the game." (Juul 2005, p. 58) Extending this argument to the *Game of Life*, however, one could easily satisfy Juul's definition of games simply by adding external physical input, even if that input is not based on any player interaction.

Unfortunately, Juul (2005) has omitted an important aspect in his analysis. An automaton[20] need not have a finite number of states, or even a countable number of states. In probabilistic automatas (PAs) (Rabin 1963, pp. 230-245) stochastic transition functions are non-deterministic. Also other non-finite state machines like quantum finite automatas (QFAs), an encounter in quantum computing, can have an uncountable infinity of states. Could these be used as game physics elements? I posit that the unbounded nature of such state machines does not prohibit their use in computer games, because even the simplest of games already generate a state machine with billions of possibilities. For example, the early computer game *PONG* (Atari, 1972) is very rich in states[21] despite its simple gameplay and technical limitation, a fact that was probably one of the reasons for its commercial success.

[19]The Game of Life is a cellular automaton devised by the British mathematician John Horton Conway in 1970. It is the best-known example of a cellular automaton implementation and is generally regarded as game, where one interacts by creating an initial configuration and observing how the graphical representation evolves.

[20]An *automaton* is a mathematical model for a FSM in this context.

[21]In order to calculate the number of possible states of the *PONG* state machine, one assumes the game is played on a 160x192 pixel screen of the Atari VCS 2600 game unit (popular in 1976). We have two x-variable elements with the paddle graphics and one xy-variable element in the ball graphics which are all free to assume any position on the screen. Thus the number of possible game states can be calculated as 160*192*160*160 (neglecting the position limitations due to the size of the game elements) which ends up to be approximately 3 Billion game states.

From the player's perspective, most current games have even greater degrees of freedom and therefore essentially represent infinite state machines. This means that while computer games tend to reduce overall game play to a more limited finite state machine through the game designers' use of progressive levels,[22] they almost always provide infinite state machines through their dynamics simulations. Thus, for many computer game implementations, Juul's analysis is misleading when he states that "action games can also be seen as game trees, but with a much larger number of branches." (Juul 2005, p. 61) Furthermore, he fails to recognize the value of complex systems in games, which allow for faster content creation on the production side and enable emergent gameplay from player interactions. He also fails to recognize that complex systems may lead to additional self-expression of players during gameplay, which is another value from a game design perspective. Thus, the search for new game physics elements should select complex systems in physics and prefer ones that form non-finite state machines.

In the above paragraph I discussed Juul's (2005) FSM analysis for game rules and pointed to a method for expanding games with elements that increased the number of states by adding complexity. As discussed before, computer games have already made successful use of random number generators to increase the topography of the state machine by injecting random numbers as input. By omitting a discussion regarding possible issues arising from the usage of PRNGs in computer games, Juul has missed an important point. After all, the only way to create truly random numbers is to actually measure values from a random physical process.[23] Therefore, new

[22]This is storytelling or fictional control that game developers impose on players as they move from stage to stage.

[23]Random number generators used on computers are not truly random but are simulations of randomness which are completely determined by a relatively small set of initial values. Many traditional games such as cards, dice and the roulette wheel, but also many forms of physical sports, are macroscopic random number generators. The unpredictability in these games is due to the properties of unstable dynamical systems and physical randomness present in all these games.

game physics could focus on adding physical randomness and making use of rule-systems that create complexity or add physical randomness.

4.3.2 Koster – Fun in Game Design

As the title of Raph Koster's book *A Theory of Fun in Game Design* (Koster & Wright 2004) indicates, the origins of the "fun" that players experience when engaged in play tends to inform computer game design. While Koster recognizes the contributions of game theorists such as Huizinga, Caillois, Juul, and Salem and Zimmerman, he quickly dismisses their findings as inadequate for the work processes during practical game development. He then proceeds to define methods of *fun-creation* in game design. He initially cites comments from leading game developers such as Chris Crawford, who states: "Games are a subset of entertainment limited to conflicts in which the player works to foil each other's goals." Others such as Sid Meier[24] define games as "a series of meaningful choices," or in case of Ernest Adams[25] as "one or more causally linked series of challenges in a simulated environment." Koster's own theory is based on the notion that games are cognitive puzzles for the brain. His easy-to-read definition of games is quite similar to other theories that serve to verify the effects Koster describes as "a resolution of optimum discrepancy."[26] I posit, that research in physics is at least in part a "cognitive puzzle" as Koster describes it, and new game physics elements may need to address the relationship to fun and entertainment in this way to gain acceptance from players.

In order to construct an effective game physics element using the idea of

[24] *Sid Meier's Civilization* (1991, Micro Prose) is the first game in a series of a turn based strategy computer game created by Sid Meier. The games in the series are some of the most successful strategy games of all time.

[25] Ernest Adams is a game designer, co-founder of the International Game Developers Association, as well as a regular lecturer at the Game Developers Conference (GDC).

[26] See also Heckhausen's similar discussion on activation cycles in section 4.2.4.

a "cognitive puzzle," one needs to ask: Where does *fun* actually come from? Cognitive theory points to a common property of perception called "chunking," which automates the recognition of patterns and organizes items into familiar manageable units. This process drives our preference for textured order. Conversely, any pattern we do not understand becomes noise. Therefore, for Koster, games and reality are equivalent and essentially puzzles for our brains. He posits that games are abstracted and iconic, thus readily absorbed because the formal systems they develop "assist in excluding distracting detail." (Koster & Wright 2004, p. 36) The act of solving such puzzles causes a biochemical reaction in the brain – the release of endorphins – that turns them into fun for the participant. The opposite effect occurs when the brain is either over-stimulated (noise) or under-stimulated (silence); and games that fail to train our cognitive abilities are often deemed as boring. If chunking is the process of reducing a potentially complex set of rules into a single conceptual unit, for Koster, *art* is an illustrative example of the opposite process, because "art could be seen as a means to offer the viewer a way to break out of pre-conceived chunking." This idea has motivated me to conduct an analysis of videogame and science art (section 5.3 and 5.4) in order to find novel ways for a game to train players in physics-related "chunking" and thereby create new "cognitive puzzles" from game physics.

As Koster further posits, boredom, irrespective of frustration or triumph, arises when one of the following occurs (Koster & Wright 2004, p. 44):

- The pattern has been fully learned by the player.
- The pattern permutations sink below the player's level of interest.
- The player fails to see the pattern and perceives it as "noise."
- The change of pattern variation is too slow or too fast.

Finally Koster adopted game designer Ben Cousins' definition of 6 *ludemes*

as the basic units of gameplay that need to be incorporated into a "fun" game:

1. Preparation (otherwise it is all based on chance)
2. A sense of space (otherwise it is a trivial game)
3. A solid core mechanic (otherwise there is no game)
4. A range of challenges (or the game exhausts itself quickly)
5. Varieties of abilities required to solve the puzzle (or it is too simplistic)
6. Limited skill required in using the abilities (or it is too tedious).

Furthermore he states that to achieve learning in the game, one must also embed three additional methods: variable feedback (i.e., "Did you do it well or poorly?"), a main problem and a cost-measure[27] for failure (Koster & Wright 2004, pp. 120-122).

As evident from this analysis, knowledge of the "mechanics of fun" can be very useful when constructing new game physics elements. However, several limitations can be identified in Koster's (2004) analysis. For example, he forgot to mention how formal systems play an important role. One can observe that children and animals often learn without "fun maximization" in order to acquire the basis of game patterns – formal systems – which are needed for engaging in play.[28] Furthermore, why is any input without relevance deemed to be seen as noise by the player? Koster's statement that frustration always comes from noisy patterns, which should therefore be avoided, eliminates the possibility for a game designer to consider creating mental connections between the player and the patterns in the first place. Could it be that the player also needs to be sensitive enough to experience the phys-

[27] As players progress in a trial-and-error way, the game needs to provide a way to estimate when progress is made. Koster and others argued that this approach can even be applied to game development itself (Koster 2008).

[28] See epistemological studies by Jean Piaget and others.

ical disturbance of a subtle input? Unfortunately, Koster failed to mention the connection to rituals as well as work, both processes that are often inherent parts of games. He also makes an argumentative mistake when linking game capabilities directly with our intellectual abilities – equating the fact that "the level of mathematical sophistication required by games has risen dramatically over the course of human history, as common people learned how to do sums" with the fact that "games are very good at quantification." (Koster & Wright 2004, pp. 62-63)

Koster's reduction of play into a 1-dimensional physiological model of fun maximization may be motivated by his game industry involvement. Koster's notion that "games are not about the beauty or delight of aesthetic appreciation, because delight is about the momentary recognition of patterns and does not last" (Koster & Wright 2004, p. 94), fits the game industry's focus on the entertainment of the masses and the industrialization of fun. It breaks with other game theorists' ideals which have been discussed earlier, where more ephemeral and meaningful games are scrutinized (see section 4.2.1). He disregards Kant's (1781) philosophy, which clearly reveals that perception and enjoyment can occur at very high levels and that the repeated view of an image is possible without boredom and frustration. According to Kant, whereas the *initial fun* may instantiate at a lower level, the appreciation of the work increases with repeated viewings, leading to a form of *aesthetic fun* which processes information at a much *higher state of mind* than pure puzzle-solving. So it is especially the level of "aesthetic fun" which new game physics should aim for, by enabling free play within physical simulations or by creating new perceptive models that emphasize the aesthetics of the physics structures themselves. Such an approach might also elevate the experience of fun to intellectual levels that are required for a learning experience.

Interestingly, Koster's (Koster & Wright 2004) own analysis provides some hints on how this could be achieved. Formally constructed games are for

Koster "limited and need to incorporate less predictable variables." This is comparable to one of Caillois' (1962) observations: *agon* and *mimikry* shuffle players and audiences perception respectively, which, when applied in computer games, provides random input to games in genres based on these two principles. Physics simulations or physical systems are one of these less predictable elements and Koster actually prescribes them for games when he proposes: "If games are essentially models of reality, then the things that games teach us must resemble reality." (Koster & Wright 2004, p. 52) I agree with this observation by Koster, and this dissertation will explore practical game designs that help to model reality. His analysis of game development for 2D shooters (see figure 4.3) also points to a simple method for such game innovation by repeatedly finding "a new dimension to add to the gameplay." (Koster & Wright 2004, p. 78) Therefore, new game physics would need to provide such "dimensions" to the gameplay not just to improve existing game mechanics or interfaces, but also to fundamentally shift and extend gameplay. Again, as the practical work, I will attempt develop examples that extend game design with new, previously unused *dimensions* based on physics.

One of the aims of this study was to re-think game design through the introduction of new game physics. Koster (2004) offers contradicting clues in his text about the impact of such a modification. On the one hand he warns against too much freedom, because "innovating out of a pattern is by definition outside the magic circle," and he proclaims that players "don't get to change the physics of a game." (Koster & Wright 2004, p. 116) On the other hand he encourages innovation and demands that "games are placed in context with the rest of human endeavor so that game designers can feel comfortable venturing outside their field in search of innovative ideas." (Koster & Wright 2004, p. 138)

In the chapter entitled "The Ethics of Entertainment and Where Games

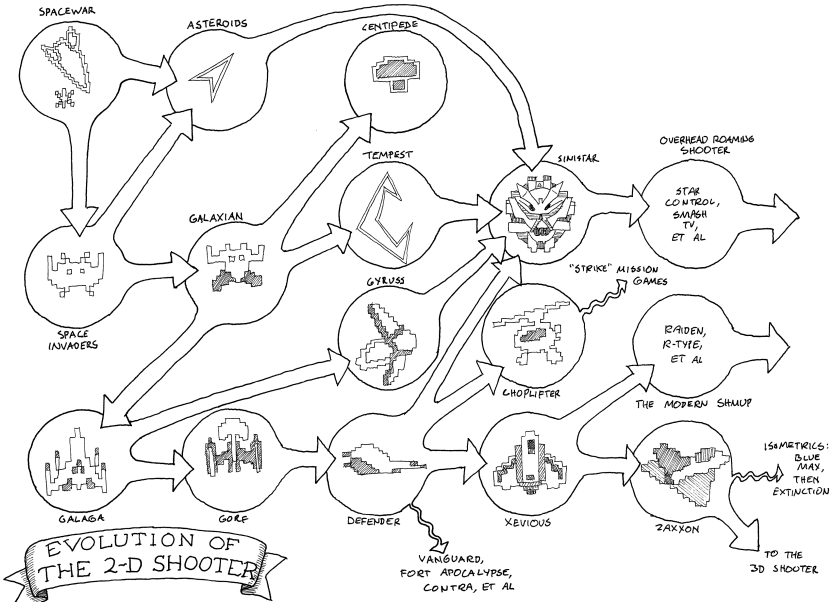


Figure 4.3: Koster's *Evolution of the 2-D Shooter*; each game represents a new avatar control paradigm (Koster & Wright 2004, reproduced with permission of author)

Should Go," Koster's (2004) discussion was very informative for this research. Ethical attacks on the depiction of violence in games, for example, are aimed at what he calls the "dressing" and not at the core game-mechanics themselves. He argues that the influence that games exert on the player comes from the core of the medium, the game mechanics. He concludes that games are immune to such ethical attacks aimed at the "dressing," because they train players to ignore the fiction or metaphors that envelop the patterns built from the game-mechanics abstractions. (Koster & Wright 2004, p. 80) As a result, gamers are dismissive of the ethical implications of games, because they think that games only train the essential underlying mathematical patterns (Koster & Wright 2004, p. 84).

In my view, game designers and players should disagree with Koster's view

that games primarily teach us things that we can absorb into the unconscious – fairly primitive behaviors – as opposed to things designed to be tackled by the conscious, logical mind (Koster & Wright 2004, p. 76). His view on what games can offer is dim, when he posits that "games thus far have not really worked to extend our understanding of ourselves" and "any form of entertainment is about sex and violence." (Koster & Wright 2004, p. 174) Should one make games that better portray the human condition? The obstacle to overcome for Koster, is the state of mind, attitude, worldview and intent of the player. Perhaps game physics can be both close to the game-mechanics of a game and also important for the general worldview of the player. Therefore, I argue that by improving game physics a possible solution to the stated dilemma could be found – one which may help to determine the future of games and their development practices.

4.3.3 Gee – Games and Learning

Another aspect to consider is how game theorists analyze learning through games. Many computer games about science or physics are developed for schools or used in an educational context, and in 2003 the linguist Paul Gee opened up a discourse about such games in his well-known work *What Video Games Have to Teach Us About Learning and Literacy* (Gee 2003). For Gee, the connection between computer games and cognitive development was based upon how an individual develops a sense of identity, how he/she grasps meaning and evaluates or follows a command, how he/she picks a role model or perceives the world, all in relation to computer games. Since each of these aspects are also applicable to game physics, the connection between Gee's book and this study is straightforward: How might game physics influence the players' scientific understanding and world view through the games that they play?

Gee (2003) summarized the content of computer games into a dense set of definitions. For him, games create "*situated meaning* in a multimodal space through embodied experiences which allow players to solve problems and reflect on the intricacies of imagined worlds and of both the real and the imagined social relationships and identities." He introduced the term *semiotic domain* to describe this situation created by the game for the player.[29] For Gee, the meaning of language, symbolisms and multimodal media are always *specified* for a situation, thus must be part of a particular semiotic domain. Physics for example is seen as a rigorous domain, and traditional schooling in physics tends to revolve around content, facts and principles of that domain,[30] rather than learning through fun. Thus physics education is traditionally more passive in nature and seldom involves artistic approaches.[31] A better method for communicating and teaching physics would be active learning, which involves the process of experiencing the domain in new ways and forming affiliations with it. Such an approach in the future may prepare students to learn more and empower them to be critical about physics. Through these processes, the active learner can enter a particular semiotic domain. As Gee argues, computer games are excellent tools to create such situated meanings through "embodied experiences that are mediated via the artificially created domains." (Gee 2003, pp. 22-26) For the purpose of teaching physics via active learning, computer games could be one of the best educational tools available, and therefore it is important to take a closer look at Gee's principles.

[29]Gee gives many non-game examples of his broad concept on *semiotic domains*, such as: cellular biology, postmodern literary criticism, FPS computer games, advertisements, Roman Catholic theology, modernist painting, and even midwifery.

[30]Key properties of semiotic domains are the recruitment of one or more modalities to communicate distinctive types of messages, the formation of a design grammar, and the association with an affinity group (Gee 2001).

[31]A good example of such approaches is the seminal video *Children's Tapes* by Terry Fox (1974) which is based on elementary experiments that illustrate fundamental principles of physical science to create "phenomenological dramas." (Electronic-Arts-Intermix 1997*a*)

Actually, Gee (2003, pp. 48-50) posited that there are 5 principal aims for good educational games: *a*) to encourage active and critical learning; *b*) to focus on the design principle; *c*) to employ a complex semiotic fabric; *d*) to connect semiotic domains; and *e*) to employ metalevel thinking between connected domains.

If one translates these aims into design goals for computer games, the results yield three observables for Gee. First, games can become self-reflective or "life-enhancing experiences." Second, the learner tends to fall back on the simplest and easiest tasks. Gee, in his role as an educator, emphasizes therefore the importance of finding ways to enhance "hard things" in life. Finally, the economics of computer games tends to lead to a "Darwinian selection" of games: the ones that have good designs for teaching hard and challenging things are the most popular, regardless of the game genre. In this way, games could be used as prime examples for the best learning theories in cognitive science (Gee 2003, p. 6). In particular, Gee's second realization about computer games – on making difficult things easy for the user – points to the possible challenges one faces in matching physics to a game. Physics can be a very difficult subject which requires a wide range of background knowledge; however, if one were to construct semiotic domains in a game about physics as a teaching tool embedded inside new models of game physics, the process may bring about an important understanding of how to build meaning specifically for that domain. I will now attempt to deepen the analysis in this direction.

For Gee (2003), semiotic domains match internal and external views. In other words, content (the internal part) is often made by real people with social interactions (the external part). It is important to note that there is always a cross-influence between these two views. Furthermore, semiotic domains are always governed by what Gee calls *design grammars*, a combination of rules and normalizations. These grammars define identity *within* the do-

main as well as association between the domain and an external affinity group (Gee 2003, pp. 30-36). Design grammars change over time, particularly in computer games where computing platforms improve rapidly in accordance with *Moore's Law*.[32] Therefore game design tends to respond with "fashion trends" that are constantly changing. Because those changes proceed more rapidly in game design as compared to most other fields of human activity, computer games are particularly interesting for young audiences.[33] Thus, to maximize the ability to reach such audiences, it follows that new game physics should be aware of the trends within the player community itself. Perhaps designers may go a step further and market game physics as a new "fashion trend" in game design to gain acceptance.[34] However, the approach may provide only a short-lived impact, as such game physics could become quickly unfashionable as well.

In Gee's (2003), analysis, the learning practice in a semiotic domain consists of a cyclical, four-step process: probe, hypothesize, re-probe, and rethink. This only seems logical, if one treats the mind of the player as a general pattern recognizer, because this cyclical process is simply a self-training exercise for his or her neural network.[35] Since humans engage with this process constantly, interconnected and associated sets of patterns may tend to reshape the experience we have in our mind. However, as the player's

[32]Moore's law is the empirical observation that at our rate of technological development, the complexity of an integrated circuit, with respect to minimum component cost will double in about 24 months.

[33]Especially young people, enjoy the diversity that changing fashion can apparently provide, seeing the constant change as a way to satisfy their desire to experience "new" and "interesting" things.

[34]Such a trend was observed when the XBox console was introduced (see figure 3.10).

[35]The term *neural network* is referring to a network or circuit of biological or artificial neurons. The concept is also used in neuroscience to make a link between observed biological processes (data), biologically plausible mechanisms for neural processing and learning (biological neural network models) and theory (statistical learning theory and information theory). Artificial neural networks are viewed as simplified models of neural processing in the brain; they have been applied successfully to speech recognition, image analysis, adaptive controls, to construct software agents and autonomous robots.

mind tries to generalize these patterns constantly into experiential theories, his/her semiotic domains need to be *embodied* in order for these patterns to be useful (Gee 2003, pp. 90-96). An embodiment is created and matched by the appreciative system of the player or participant during any evaluation in the four-step cycle. Thus matching the user's expectations of physics with new game physics elements could become a key component of the critical learning process, and further applications in this direction need to be tested.

Gee (2003) cites additional benefits of computer games apart from their facilitation of active and critical learning. First, games form a social space for players and non-players around the learner that help him or her in the initiation and propagation of meta-reflective thinking about the game itself and its interrelated domains. This fostering of critical thinking within and beyond the domain is in fact deemed more valuable than *pure* active learning. According to Gee, thinking in extended and connected domains is central to a functioning process of active learning and not just an "add-on." Second, games typically connect to *other* semiotic domains. For example, precursor domains can facilitate the mastering of a computer game, which in turn can be designed to be a precursor for other domains (Gee 2003, pp. 46-48). Therefore it is possible to design game spaces, activities and problem-solving that will relate to learning in domains like science, especially if an active learning process is included and not just the task of rote memorization. As findings from interviews of game-players by Gee and others have indicated, the current crop of games do serve as precursor domains for mastering computers and related technologies for young people. Similarly, new game physics could be designed in such a way to form precursor domains that are specific to physics. However special care must be taken that such implementations of physics domains remain useful as it is my belief that pseudo physics found in many current computer games can actually hinder learning.

Gee (2003) also discusses the notion of identity in virtual game worlds

and finds it to be tripartite: virtual, real-world and projective. By this he suggests, that learning involves an identity shift from one semiotic domain to another in the same tripartite way. For example, a student in a science class could take up a set of cognitive and social practices to actually assume the virtual identity of a "scientist" in a game. Then the computer game context would be designed to transport the user not only into a virtual but also into a new contextual role. Next, the learner would need to bring the real-world identity into the process so that bridges can be built from one identity to another. In this way computer games can be instrumental, as they could encourage the user to try harder while at the same time projecting continuous success to motivate the player. Thus, a learning space is created where risks have no real-world consequences – or, as Erickson calls it, a *psychosocial moratorium*[36] is created. This moratorium would open up the possibility to use new game physics to conduct simulated experiments of real physics that might be risky, dangerous or contain far-reaching implications. The player could, for example, explore practical applications such as real space flight, nuclear reactions, or global climate change in this way, all prime topic areas and relevant learning scenarios in physics.

The perception of a traditional "story" in a movie or book is often a combination of the writer's aim and the viewer's or reader's imaginative projection about the plot, characters and environments described in the story. Computer games can add two more components to such traditional narratives: the player can change the order and content of the plot and players can be direct participants in the storyline. Gee called this potential property of computer games "embodied stories" (Gee 2003, p. 83), which typically require a substantial personal emotional investment during gameplay. However, both

[36] *Psychosocial moratorium* is a term formulated by German psychologist Eric H. Erickson and further extended by Sherry Turkle to the Internet, as a time during which a person can retain a fluid identity and occurring from early pre-adolescent to adolescent life in modern industrial societies.

past and current computational capabilities do not allow for the creation of completely player-directed storylines at the same level as author-created stories. Instead, a well-defined dramatic structure and realistic conversations are often replaced with embodied stories that utilize motivational elements, first-person narrative and situation-specific symbols in "situated meanings." In game physics, formulas and their numerical properties could become such symbols and used as embodied and situated parts of a storyline. One good example was the aesthetic effect and impact on the viewers created by a computer rendering of "fractals"[37] that not only became a popular topic in then 1980s, but also represented a powerful symbol for the power of mathematics. Therefore, I posit that new game physics does not always have to be an active algorithm or interactive simulation, but could also be a "scientific story" – one that might even be written in the language of mathematics, a characteristic aspect of physics (see Appendix B).

But how could an abstract symbolism, such as a fractal, become acceptable or even enjoyable to players? It is important for learners/players to embody situations that can enable them to distinguish contexts of science domains. This process is routine work for experts who already have embodied experiences about the relevant equations and can effortlessly capture the principles at a more abstract level. Metz & Hammer (1993) have shown that one method to achieve such a learning effect even for non-experts is to make "programming" one of the methods of play in a game.[38] According to their

[37]Fractal geometry describes many situations which cannot be explained easily by classical geometry, and has often been applied in science, technology, and computer-generated art. Famous imagery can be created for example by computation and plotting the *Mandelbrot Set*, which is defined by the following simple iterative process in the complex plane: $z_0 = 0\, z_{n+1} = {z_n}^2 + c$

[38]A programming language called Boxer developed by H. Abelson and A. diSessa was used. Boxer is a visual language, which claims to be the successor to Logo where boxes are used to represent scope. It is a language whose main purpose is not necessarily education in physics but it has been used with students to help develop conceptual understanding in force and motion using physics-related "Microworlds."

research, the abstraction needed for programming requires the player to construct and maintain projections of the real-world entities being modeled in code. These projections are finally "consumed" in the act of playing. Their research also showed that the formation of such projective identities by the player was enhanced by using simpler "mixed languages" in the game. For example, one language addresses the virtual character and another instructs the player about game controls (Gee 2003, chap. 5). In the same manner as Gee confirms, new game physics should form subdomains that are simpler in construction and easier to access by the learner/player. Such game designs could, for example, deconstruct actual domains of practiced science and create much simpler subsets that allow the player to interact by *programming* the physics contained in the game.

Finally, Gee's (2003) text serves as an illustrative example of how "fuzzy" scholars in the humanities tend to treat physics. In his book on computer games and teaching he argues that there are two things that, at first sight, look to be *mental* achievements, namely literacy and thinking. However, he continues to point out that they are also, in reality, primarily social achievements[39] (Gee 2003, pp. 1-2). In order to illustrate this point, Gee makes an example using the physics definition of "work" and relating it to the everyday usage of the same term. Unfortunately, he does not use correct physics as his definition of "proper physics."

> In the world of physics, ... if you have pushed your stalled car until you are dripping with sweat but the car has not budged, you have done *no work* (given how physicists use the word).

As any physicist can attest, this statement is false, because some work is still

[39]His conclusion is similar to an earlier argument by L. Wittgenstein against the possibility of using "private languages," reading (new literacy studies) and thinking (situated cognition) *in isolation* to enhance learning.

done through a minimal compression of the springs, tires and even the ground the car stands on. Gee's mistake is the simplified assumption that *visible work* in relation to the displacement of the car is the *only* process here. I think the example illustrates well how simplified physics can negatively impact an otherwise valid discussion.

4.3.4 Galloway – Algorithmic Cultures

All game theoretical literature reviews so far have complemented the cultural discussion started by Huizinga (1950) (see section 4.2.1). But what about considering computer gaming itself as an independent medium? As writings by media theorist Alexander R. Galloway (2006) explore, games have become visually and conceptually sophisticated spaces where players inhabit detailed worlds and manipulate digital avatars with a vast array of actions and choices. He considers the computer game as a distinct cultural form, comprised of unique *algorithmic cultural objects* that demand a new and unique interpretive framework (Galloway 2006, p. 86). In the context of this study, Galloway is a practitioner rather than a theorist; thus he brings a unique perspective to this review of game theories and forum comments.

Galloway (2006) studies computer games because they are embedded "in the information systems of the millenary society" and believes "this medium will likely remain significant for some time to come." Since Galloway has a great deal of experience in research and artistic practice using software as an action medium, games are a natural focus for him. However as is apparent from the comment that "one must always remember that computer games are software *systems*," he remains critical towards treating software as *just* an algorithmic artifact (Galloway 2006, pp. 2-6).

For Galloway (2006), this definition of software is borrowed from Hechen-

berger (2004) who thought of the computer as a type of machine for converting meaning into action, and he makes a straightforward connection between the concept of "action" and games through the introduction of the term *gamic action*. According to Galloway, computer games *are* actions; they only exist when enacted. "To understand computer games, then, one needs to understand how action exists in gameplay." (Galloway 2006, p. 3) Reflecting back on the shortcomings of existing game theories, he observes a need to define four new "moments" based primarily on the concept of action. These *gamic actions* exist as a unified, single phenomenon in all computer games and create a classification space. In Galloway's 2D scheme, a horizontal and vertical axis define the *Machine vs. Operator* and *Diegetic vs. Non-diegetic* continuum of actions, which he defines as follows:

Machine actions are performed by the software and hardware of the game computer.

Operator actions are performed by the player.

Diegetic actions are story-actions based on the same term adopted from literary and film theory. The diegesis of a computer game are the elements of narrative action, i.e., on- or off-screen characters and events, the elementary play situation.

Non-diegetic actions are very common in computer games because non-diegetic play elements are all things external to the narrative action, i.e., titles, heads-up-display, start and pause buttons.

Having normalized *gamic action* in this fashion, distinct quadrants (see figure 4.4) can be identified as the 4 *moments* of Galloway's theory, which I have summarized as follows:

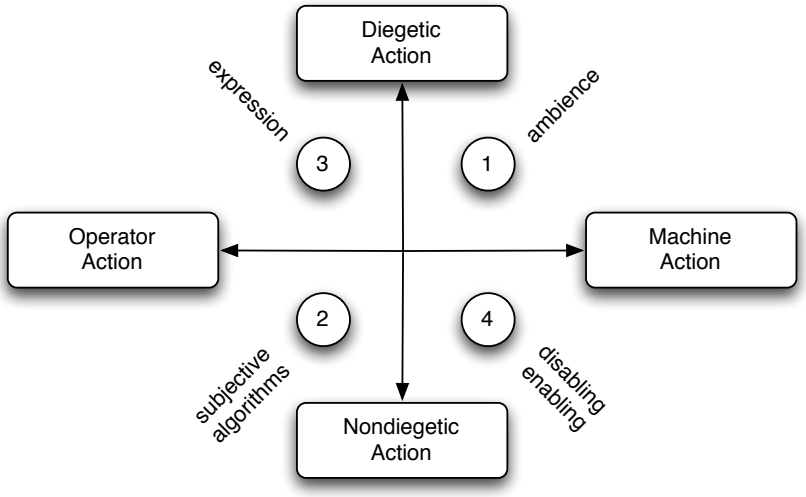


Figure 4.4: Galloway's 4 moments: a classification scheme for *gamic actions* as quadrants; adapted from Galloway (2006, p. 17)

1. **ambience**: The games settle into a moment of equilibrium when left alone and play is absent; the operator is momentarily irrelevant; this moment's only purpose is a "charged expectation" of the possibility for the operator to return (Galloway 2006, p. 11). This is the ultimate fetishization of the game; but at the same time this is the most non-gamic action.
2. **subjective algorithms**: The action of pushing pause, applying cheats or game hacks, setting up action, selecting players. This quadrant defines a whole class of games where the act of configuration *is* the gameplay (i.e., resource simulations, real-time strategy). The actions of this moment are important as "an allegory for the algorithmic structure of today's informatics culture." (Galloway 2006, p. 17)
3. **expression**: The direct operator action inside the imaginary world of game play. This moment couples the acting agent with actionable objects (ammo, monsters, etc.). Usually these actions are deeply con-

nected to game-controller design. The theories of Huizinga (see section 4.2.1) and Caillois (see section 4.2.3) both focus almost exclusively on this quadrant, a fact that limits their usefulness in computer game analysis (Galloway 2006, p. 21).

4. **disabling/enabling**: These are all actions by the machine that enrich or degrade gameplay. In particular there are *disablers* such as the "game over" event, software bugs, and performance lags, and *enablers* such as power-ups and level goals. A third class of actions in this quadrant are "machinic embodiments" which appear in forms such as bytes visible as pixels, or structures introduced by the Object Oriented Programming (OOP)-nature of the game software.

The importance of the non-diegetic machine act (4) is emphasized by Galloway (2006), and is caused by the ambiguity between the outside and the inside of a game. It creates brief moments of "unplay," which does not destroy the game but actually elevates it to a higher form of play (Galloway 2006, p. 35). According to Galloway, media artists engaged in "Countergaming" productions have realized this opportunity through their game modifications. "Most artist-made computer games are mods[40] of game technologies (whether at the visual level or at the game physics level), not mods of actual gameplay." (Galloway 2006, p. 108) He posits that "aesthetics are elevated over gameplay; realms often modified by artists are: space, visuality and physics." (Galloway 2006, p. 118) Although Galloway's text is by no means conclusive in its scope, it points to a possible shortcoming of some videogame art, in that artists' approaches to computer games often remain limited because many possibilities that computer games have to offer are left unexplored. Since this dissertation suggests that transdisciplinary teams provide value for game design, I will explore the reasons for such limitations

[40] *Mods* is a common abbreviation in game player circles for the word 'modification. A *mod* refers to the change of existing game engines or data to create a new game or gameplay that is different from the original.

again in section 5.3 on videogame art.

Since Galloway (2006) cites physics, could game physics be a topic for artistic expression? Galloway's analysis contains a discussion on "natural vs. invented physics" in computer games, which might shed light on this question. In particular he makes the following claims: (a) *Bullet Time*[41] breaks Newton's law; (b) JODI's *Untitled Game* (JODI 2001) introduces a set of counterintuitive, entirely invented physical laws; (c) blurring effects in *Adam Killer* (Condon 1999) or *QQQ* (infothetics 2005) employ an invented physics of visuality. Unfortunately these claims are incorrect. *Bullet Time* actually heightens the display of physical reality by increasing the accuracy of the simulation; *Untitled Game* does not change physical laws, but simply modifies the 3rd moment (operator diegetic action); and the "invented physics" of *QQQ* is merely an implementation of the 4th mode as a machinic embodiment of the display system. In conclusion, game physics was never really used as an element of artistic expression in any of Galloway's examples.

Although Galloway's (2006) concepts of physics are underdeveloped, he does make a convincing point when he rhetorically asks artists to "create new grammars of action and create alternative algorithms" (Galloway 2006, p. 125) in order to advance gameplay. By designing new game physics elements, this dissertation may provide some new facilities for the inclusion of game physics in a more artistic context.

[41] So called *Bullet Time* is a variable speed method of photography used in recent films, broadcast advertisements and computer games which is characterized both by its extreme permutation of time (slow enough to show normally imperceptible and un-filmable events, such as flying bullets) and space (by way of the ability of the camera angle to move around the scene at a normal speed while events are slowed). It is usually a computer generated effect which was popularized in the movie "The Matrix" (1999).

4.4 Chapter Conclusion

As the preceding literature review of game theorists has shown, there are many points to consider when analyzing game physics and defining new game physics.

Not only are computer games culturally important but also game physics found within them needs to be disambiguated in order for it to become a useful resource (Huizinga 1950). According to the analysis conducted during this review, computer games have neither reached their potential as educational helpers nor as experimental tools in the sciences (Gee 2003, Koster & Wright 2004). This may be due to the limited nature of existing game physics. The analysis of several theorists shows that pseudo physics in games is partially caused by a lack of background, implementation challenges and a fixation on interaction-fidelity by game developers (Juul 2001, 2005). Furthermore, scientific research that is conducted in terms of "free play" scenarios may be interesting to players as well as scientists. For such a usage, adult players require special considerations in order to maintain interest, whereas younger players can be motivated through the creation popular trends (Gee 2003, Heckhausen 1973, 1989).

As this dissertation proposes, a significant enrichment of games can be achieved by adding new dimensions through new game physics (Koster & Wright 2004, Scheuerl 1954). Game physics should attempt to become a group-forming activity – an action that may bridge disjointed communities such as game players, scientists and artists (Gee 2003, Huizinga 1950). However, user expectations need to be managed and sub-domains constructed when deploying new game physics (Gee 2003). Artistic interpretations of game physics can also advance gameplay, and artists should be taught the basics in order to do so (Galloway 2006).

The development of new game physics can be guided by several theoretical principles. Some of the key ingredients in computer games, such as ambivalence and complexity (Caillois 1962, Scheuerl 1954) or random number generators (Juul 2005) are not used to their fullest potential unless physics is also introduced. However, when physical complexity has been integrated into a game, it is not appropriate unless repetitions are avoided (Scheuerl 1954). Standard game physics is generally used in a competitive context to introduce *vertigo* (Caillois 1962), which may be extended to become a mental rather than a physical exercise. The mechanisms operating in successful computer games need to be taken into account when creating new game physics. In particular game elements that create stimulation, fun and action require more attention (Galloway 2006, Heckhausen 1973, 1989, Koster & Wright 2004). Nevertheless, new game physics does not have to be an active algorithm or interactive simulation to facilitate agency (Gee 2003).

The results presented in this chapter have been coalesced in section 5.2.5 into a subset of principles which specifically leverage some of the theoretical findings. I posit, that these principles advance computer game design when physics is used as a game element. As can be also seen from the analysis in this chapter and some of the conclusive points above, game physics is not yet well addressed on a theoretical level. In fact, game theorists have many difficulties in even discussing game physics correctly (Galloway 2006, Gee 2003, Juul 2005, Koster & Wright 2004). This dissertation is an attempt to address this discrepancy, create a resource for theorists and perform a deeper analysis through experiments with actual prototypical implementations of game physics elements. However, before such implementations can be made and analyzed in chapter 6, the following chapter will first describe a design framework to guide the development of such "new game physics."

Chapter 5

Physics Elements

5.1 Introduction

The goal of this chapter is to combine the analysis presented in chapters 2, 3 and 4 to develop a set of novel game elements that specialize on one or more of the basic element types – game mechanics, game story, game aesthetics or game technology – using physics. The description of each *game physics element* (GPE) will reference analytical results captured in a list of principles derived from the preceding chapters. Additional reviews of artistic approaches will be used to complement and extend the collection of principles. Following this aggregation of guidelines, four sections (5.6, 5.7, 5.8 and 5.9) are then dedicated to the detailed development of exemplary GPEs in all aforementioned types by applying the described principles.

5.2 Designing New Game Physics Elements

This section summarizes the theoretical analysis of game physics, theories of play and quantitative analysis of physics in games, to define several "principles" – labeled as **P#** for easy referencing throughout the remainder of this chapter – in order to guide the game physics element design.

5.2.1 Principles from Science

As was described in section 2.2, physics consists of a broad collection of fields. These can provide a rich resource for game design through their description of scientific laws, measurements of natural phenomena and unique methodologies to advance knowledge. When transforming physics into computer game elements, for example by creating simulations of natural processes, several characteristics inherent to physics should be preserved to make the resulting game elements scientifically relevant, thus accessible to the physicist. Furthermore, elements should also attempt to resolve some of the key issues physics faces when communicating in the public realm. I posit that this approach makes the resulting game elements more valuable for the player.

P1 GPEs should support the application of the scientific method by creating observables in their simulation (e.g., allowing player measurements).

P2 GPEs should indicate where simulations are not physically accurate (e.g., presence of an *arcade mode*).

P3 GPEs become more meaningful if they reflect properties in their simulated objects that illustrate unity of nature such as symmetries and proportions.

P4 GPEs should liberally expose the underlying language of mathematics, which is so integral to physics research.

P5 GPEs that emphasize scientific precision and accuracy generate a quality that is sought after in the sciences.

P6 GPEs should avoid "fringe science," and instead aid in making less-known but legitimate physics research accessible to the public.

P7 GPEs should attempt to bridge the gap created by the dichotomy of classical physics vs. modern physics.

Balancing scientific rigor with the player's desire to have fun playing games will be key to the successful application of elements based on these principles.

5.2.2 Principles from Game Physics

Existing game physics elements are generally limited to the simulation of virtual space, Newtonian object dynamics and stereotyped depictions of scientists as characters (see section 2.3.2). Such "standard game physics" has been subject to trends that cause a domination of dynamics simulations (see section 2.3.4) and leads to the presence of much pseudo physics in computer games. This situation can be corrected using the following ideas:

P8 GPEs need to expand coverage of game physics with respect to all physics fields and seek ways to include legitimate science, which has not at all been used in game designs yet.

P9 GPEs should provide a way to manage the fidelity of simulations by making them controllable, quantifiable (e.g., making errors measurable) and well documented.

P10 GPEs need to mediate between physical hyperrealities and actual reality through mechanisms that allow the player to break out of the illusions created by them.

P11 GPEs should also adhere to the guidelines for *safe* movie physics (see section 2.4.4) and avoid the usage of movie metaphors.

In order to apply some of these principles, game developers need to adopt a much broader vision of what is possible in games and should actively engage with physicists during the game design process. Commercial success is likely much less predictable for game design that uses such principles; thus customer expectations and project funding would need to be managed differently than in traditional game development.

5.2.3 Principles from Practitioners

An analysis of surveys and interviews with game practitioners and scientists (see section 2.5) indicates clearly that the primary goal of most game productions is to increase immersion and entertainment value. In the gaming community, most topics in physics are perceived as complicated and useless outside the domain of science and are therefore ignored by players and avoided by game developers, even though players actually favor innovation in game physics. The following principles seem relevant to address these problems:

P12 GPEs must illustrate their contribution to game design and demonstrate game-relevant potential to developers.

P13 GPEs are more acceptable to players when they involve practical physics topics and support in-game experiments.

P14 GPEs should favor the goal of educating the public, even at the expense of accuracy.

As the principles listed here show, their is a need to control the context in which elements are introduced in both the game development and game consumption domains and not only the technical details. Nevertheless, technical details are crucially important if customer acceptance of new elements is a desired goal.

5.2.4 Principles from Quantitative Analysis

The statistical analysis of thousands of games in hundreds of categories (see chapter 3) has shown that some level of game physics is used in over 75% of all games. Game physics was also found to be intimately connected with technological advances (see section 3.1.2). GPEs must consider the computing devices being used as follows:

P15 GPEs should leverage the latest available hardware capabilities in their implementations, while still focusing on advancing scientific or aesthetic goals.

P16 GPEs need to find ways to become available on less capable, mobile devices and for the growing casual game market.

These two principles are quite practical in nature, but since they are mutually exclusive, a game designer would have to focus on either one but never both. On the one hand, elements should push hardware and software technology to its limits using game physics; on the other hand, GPE implementations and designs need to always consider existing hardware limitations which may prevent their usage on the targeted devices.

5.2.5 Principles from Theories of Play

So far, the literature review on game theory in chapter 4 indicated that game physics is not well addressed on a very theoretical level; this is a shortcoming. While computer games are widely recognized as being culturally important, they are not fully leveraged as educational tools, in particular in relation to the sciences. Many principles of play-theory can be applied to game physics, thus providing advancements in this area.

P17 GPEs should support group-forming activities and attempt to bridge disjointed communities (e.g., gamers vs. scientists).

P18 GPEs that introduce ambivalence and complexity, while avoiding repetition, are very valuable to the gameplay.

P19 GPEs should create mental challenges through the application of physics in a competitive context.

P20 GPEs used in "free play" scenarios need special considerations (purpose, background) to be acceptable for adult players.

P21 GPEs could consist solely of non-interactive physics content, if it facilitates agency and constructs semiotic sub-domains within the game.

P22 GPEs can be disruptive to immersion or based on artistic interpretations of physics, yet still be effective to advance gameplay.

All principles in this category have specific goals (i.e., disrupt immersion, free-play) or are connected to particular target audiences (i.e., player communities, artists), thus are narrower in their applicability than the previously described principles. However, each one of them also clearly indicates the need to be innovative in game design.

5.3 Videogames and Art

Art which is influenced by computer games is called *videogame art*. I posit that such artists may provide useful approaches to the development of new game physics elements. This section starts with a brief overview of game art, reviews some of its common characteristics and then attempts to critically assess any design opportunities as well as possible gaps that can be observed. I then attempt to relate these findings to the present game physics investigation by formulating additional principles for GPE design based on this review of videogame art.

5.3.1 Can Computer Games be Art?

One may question whether a computer game can be considered to be *art* at all. Some critics say computer games are not "art" because their goal- and entertainment-driven mentality would prevent the creation of "aesthetic objects" (*Merriam-Webster*) and would not produce "works to be appreciated primarily for their beauty or emotional power" (*The Oxford Dictionary*), both of which are aspects that are central to a definition of art. But according to others such as Stockburger (2007), this view is outdated. Stockburger points out that games and art share many similarities since "both are generating spatio-temporal zones, which are perceived as different from everyday life." He argues that even "the practice of playing a computer game most definitely can be regarded as an aesthetic and sometimes creative process," citing Marcel Duchamp's usage of the game of chess as a metaphor for artistic activity to support his argument.

It is easy to find artistic productions that are realized as computer games (Ploug 2005). Computer games are also becoming more legitimatized as art through exhibitions (McWhertor 2009) or other forms of recognition by

the art community (56K 2009, Silfer 2007). I therefore assume that some computer games are a modern art form, albeit one that is going through a process of refinement and acceptance since it is based on a new technology. As Martin (2007) points out, this process of acceptance is expected and quite similar to another historical precedent: art based on photographic images during the advent of photography in the mid-nineteenth century.

5.3.2 Characteristics of Art Games

Art games are often considered to be designed in such a way as to emphasize structures intended to produce some kind of non-ludological reaction in their audiences. They tend to primarily focus on creating a unique, unconventional look, often standing out for aesthetic beauty or complexity in design rather than pursuing commercial interests or satisfying entertainment and playability needs. For technology reporter Steinberg (2010), such games marry the aesthetics of painting or sculpture with the depth of film or literature and leave room for individual interpretation and personal growth. In an effort to describe distinct types of videogame art, Clarke & Mitchell (2007) use an approach that deliberately looks only at game aesthetics to distinguish their analysis from standard videogame criticism which focuses only on game design, or "game *craft* rather than game *art*." They demonstrate several characteristics commonly found in videogame art through many illustrative examples. The appropriation of videogame iconography is one of the most identifiable characteristics and includes the usage of images of game characters, landscapes created from videogames, creation of imaginary videogames and general adoption of the iconic graphical style of computer games. This characteristic "fits into a postmodern aesthetics of sampling and appropriation with its conscious – and often ironic – remixing of cultural references [and] brings together such extremes of high culture (art) and low culture (the videogame)." (Clarke & Mitchell 2007, p. 9) Another char-

acteristic can be found in those art games that use game technology in a way it was not designed to be used. Through a modification or patch, the artist can change the functional or aesthetic elements in an existing game, often to create a critical or ironic intervention. Such "modding" generally means that form and content of the artwork are intertwined, in McLuhan's sense of "the medium is the message." Several specific art mod categories can be identified, such as machinima, sonichima, generative art, performative interventions, site-specific mods and real-time performances. A third characteristic is present in art that appropriates the form or the gameplay of the videogame. Here, the production of unique and original games by artists often concern themselves with the development of new technological methods (e.g., mixed-reality games) and require "a very high level of technological knowledge" for the artist (Stockburger 2007). In this category, a distinction needs to be made between "playable art" – interactive media art which does not take into account game culture, iconography or technology – and videogame art, since the former tends to have distinctly different artistic aims as compared to the latter.

5.3.3 Artistic Strategies in Videogame Art

Based on my review of contemporary videogame art, there is little evidence that game physics plays much of a role in any of the three artistic strategies of appropriation, intervention or creation. However, videogame art can be analyzed to find artistic strategies which are also applicable to game physics; thus it may be used to augment the principles for constructing new GPEs listed previously in section 5.2.

Historically, art was considered to be representational, while today this notion is largely replaced by the idea of art as an interpretative expression of process and issue (Adajian 2008). This shift allows Adams (2007) to

argue that computer games are a distinct type of literary art, because games inevitably express narratives. In games, there is a constant tension between narrative and interactivity. This distinguishes games from other forms of the literary arts. However, games also share a key characteristic with the literary arts in that, as Adams puts it, "the object in hand is not the work of art itself." Yet, he questions his own definition as soon he proposes it, observing that "many games have no narrative aspect" and exemplifies this with the game *Tetris* (A. Pajitnov & V. Gerasimov, 1984), which he places in the realm of visual arts instead. This assessment may not be correct, since the game *Tetris* could be treated as a "kinetic sculpture," which in turn may present a narrative. This dissertation proposes that game physics becomes a narrative through its *metamechanics*: the illustrated game physics of gravity, which lets the blocks fall in *Tetris*, forms the basis for a kind of "metamechanics," a term coined by Hulten (1975, p. 16) to describe the narratives created by sculptures of artist Jean Tinguely. Here, movement is understood as an expressive possibility in itself and thus forms a narrative, although a very abstract one.[1] The argument for game physics drawn from art is therefore that GPEs can bring games into the literary arts, if they intellectualize physical motion and processes through the games' interactions and thus create an abstract narrative of the underlying laws of physics. Since the 1990's, media art has experimented with such non-linear narratives and interactions, documenting the fascination of the artists with such forms, as users became the agents of change.

Could such an approach be acceptable to game players? A game designer would probably face challenges. In her review of art-inspired game mods, curator Cannon (2007) compares computer games and film for their effectiveness in creating intellectual engagement. She notes pessimistically

[1] See similar comment by the artists in the interview "Tinguely on Tinguely"; extract from a radio debate, Radio Télevision Belge, Brussels, 13 December 1982, reprint (Hulten 1987, p. 350).

that "the emphasis on participation in computer games is considered too demanding of our lower perceptual faculties, immersing players in the pursuit of selfish, short-term goals, that are dependent on trained hand-eye reflexes rather than philosophical or ethical enquiry." If a potential game design would intellectualize gameplay via game physics, it is to be expected that the player would perceive these demands and likely reject the game. However, Cannon also points out that the success of art mods "counter these common perceptions," which may mean that intellectualizing game physics elements could be much more acceptable to players than previously believed. Value for the art community is derived from such an approach, because it creates a new aesthetic for games and gameplay which supports videogame art through the creation of abstract narratives from physical laws.

Clarke & Mitchell (2007, pp. 13-14) observe that in videogame art, the medium *computer games* may create problems for viewers of such works depending on their "games-literacy." The contextualization of the artwork depends largely on the prior knowledge of the viewer, making the works often difficult to understand and accept for the non-gamer audiences, on the one hand; and causing rejection by gamer audiences who want to fully engage with the artwork *as a game*, on the other hand. If game physics elements are exposed to audiences with disparate game or science backgrounds, the same problem occurs. A hardcore gamer may reject rigorous physics implementations that break established gameplay modes, while scientists may not accept the game iconography, narrative and aesthetics which often include negative connotations such as the depiction of violence. Clarke & Mitchell also suggest that this issue will lessen as computer game familiarity increases over time through continued public exposure to the medium. They show evidence that art games which are based on vintage computer games, with their simpler gameplay and universal recognition, are accepted much easier by players. This strategy can be applied to the design of game physics elements for the same reason. As an active intervention, Adams (2007) calls for

game reviews and industry awards that "honor aesthetic content, not merely technological prowess." I argue quite similarly, that to advance game physics and create acceptance for experimental GPEs, game physics must be subject to "genuine criticism, not merely product reviews, [and] studied, discussed and analyzed as works of art and aspects of culture."

Tiffany Holmes' definition of art games as a medium that "challenges cultural stereotypes, offers meaningful social or historical critique, or tells a story in a novel manner" (Holmes 2003), is evidence that the art community is relatively unaware of any potential that low-level game mechanics such as game physics might offer. The fact that none of these roles are directly applicable to interactive game physics is probably caused by the challenges artists face when engaging with computer games in general; the use of game physics would merely "raise the bar" further. Apart from issues related to technical challenges, artists are more likely to exhibit criticism when engaging with computer games. Clarke & Mitchell (2007, p. 9) note that such reservations towards the medium lead to a primarily conceptual art practice because "the game element of the videogame is so strong, and so problematic for the artist ... that it requires a substantial distancing effect." An indication that the technology on which videogames are built could be difficult to approach for artists is reflected in comments such as the one by new media pioneer Suzanne Treister (2007), as she describes her first experiences with computers as follows: "I was severely warned by many artists of the dangers of being *taken over* by the machine."

Therefore, rather than introducing new game mechanics or game physics, artists' groups such as JODI tend to explore "the potential for reductive techniques to impose an awareness of the cognitive processes affected by artificial physics of virtual worlds." (Cannon 2007, p. 45) In an interview with JODI, a member explains that "the action of the code becomes a very minimal aesthetic. ... We use abstraction in connection with mathematics of the code.

We are interested in how code does represent an illusion." (Hunger 2007, p. 157) GPEs can adopt a similar approach and create abstract representation of physical simulations, in particular the kind of physics simulations that are not found in standard game engines, to emphasize the behaviors of the represented laws. This method underlies the aesthetics of many Japanese videogames, as shown in an essay by Huber (2007). He posits that computer games require simulation because "behaviors must also be represented, and the representation of behavior in a dynamic system is simulation." In the Japanese aesthetics, the depiction of an object is a matter of suggestion, creating the *omote*[2] or mask. Since algorithmic forms of game physics realize objects in game space through fairly simple forms of behavior, which Huber says "conceals that which for which it stands in, while it simulates the very act of representing," GPEs may produce an *omote*. Games such as *Super Mario Bros.* (Nintendo, 1985) have popularized the genre of *Platformer* games worldwide and demonstrate that this formula can be successfully applied in game design, in this case by using a simple 2D object dynamics simulation as the "mask" for all iconic game objects.

5.3.4 Summary

From the above analysis of videogame art, the following ideas can be derived as additional guiding principles for game physics design.

P23 GPEs can apply highly intellectual approaches to simple physical laws through gamic interactions, thus producing abstract but valuable narratives.

P24 GPEs should be subject to criticism beyond technological and scientific considerations such as debates on artistic and cultural aspects.

[2] An old Yamato dialect word describing both mask and face.

P25 GPEs become more acceptable and usable to non-game developers (i.e., artists), if they use reductive techniques that expose "behaviors" rather than fully fledged simulations.

It is apparent, even from this limited list of artistic principles, that in order to advance game design, game developers must experiment much more with the medium and be open to engage in a critical debate around their games. Art practice demonstrates that a valuable cultural discourse can result from games when entertainment is not the main function anymore. I share this view and posit that new game physics can be a good vehicle for such changes in game design.

5.4 Art of Science

Could new ideas come from artists who experiment with science in their works? Shlain (1991) has extensively described in his book *Art & Physics* how artists and physicists share a common desire to investigate reality and form an "integrated duality ... two different but complementary facets of a single description of the world." While admitting that art and physics are "unique forms of language," he also points out that "the worldwide community of artists and scientists coalesce" and "offer perceptions of reality that erase linguistic and national boundaries." He argues that because of this, both artists and scientists are generally the ones at the forefront of societal paradigm changes. However, differences exist, as Russell (1931, p. 38) notes: "A fact, in science, is not a mere fact, but an instance. In this, the scientist differs from the artist, who, if he deigns to notice facts at all, is likely to notice them in all their particularity." This section attempts to analyze physics art, contrast the artistic and the scientific approach, and extract lessons that can be applied to formulate additional principles of GPE design.

5.4.1 Analyzing Physics Art

In order to continue the investigation of principles that can be derived from the intersection of art and science, a review of selected *science art* – artworks that involve physics and that have been realized through multidisciplinary collaborations – will be conducted in this section. How can such a review further research into game design elements? A key argument is based on the observation that art can be a precursor to scientific advancement. Shlain (1991, chap. 8 & 9) illustrates how the "discovery" of Riemannian (non-Euclidean) curved space in the art practice of E. Manet[3] provided ways to *see* a facet of nature before science even began to *think* about it, by developing the necessary mathematical formalisms needed to define Einstein's general relativity theory about 50 years later. In this example, art provided insights that challenged classical physics and its rigid concepts of space and time. I posit that GPEs derived from art may present a similar "prescience" that could help to advance physics.

Science art often applies physics outside the traditional science context of the lab or of the experimental method. Accordingly, the "physics" in the art has undergone a transformative process. Could this process be analyzed to extract novel methods and points of view which are applicable to game physics? Indeed, I believe this to be true. Science art that challenges the "rules" of art by applying scientific principles may be particularly useful in a game design context, because it possesses such a great potential for inventing novel approaches. This section will therefore attempt to locate processes and methods in which science is applied through artistic practice to examine, create and transform the rules governing the emergence of art itself. I am convinced that science art provides a good source from which to

[3]Traditional perspectives and verticals are abandoned in many of Manet's works such as *Le Dejeuner sur l'herbe* (1863) or *Music in the Tuileries* (1862) in favor of a completely new organizations of space.

either formulate additional principles for GPE design or to derive new ideas for concrete GPE implementations from the works of artists.

A supporting reason for the approach is an identifiable gap in the videogame art, as discussed in section 5.3. It was found that none of the art-games cited in the reviews of Stockburger (2007) and others, feature science topics or scientific characteristics such as precision or measurability. Artists who produce art games and actively use the defining characteristics of computer games – that is, their potential to create unique experiential spaces – could therefore be well supported with GPEs that contain rules derived from the science art context. This approach would then not only help to come up with new GPEs, but also feed ideas back into videogame art and empower art in general to deal more sincerely with physics.

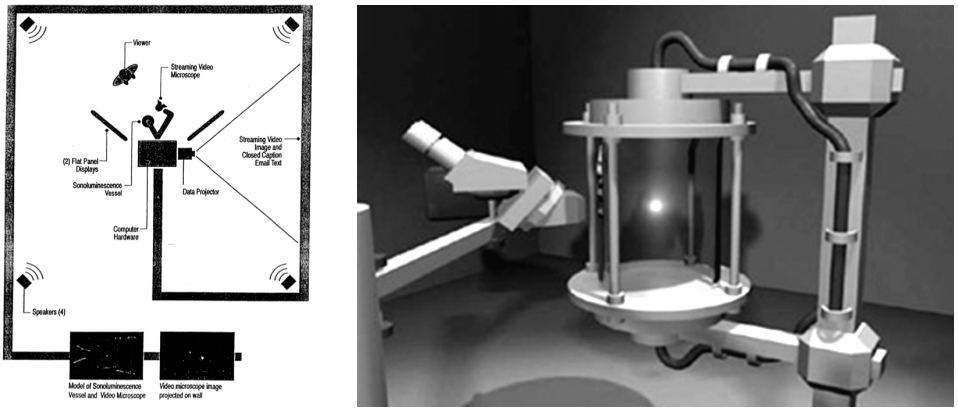
5.4.2 Selected Physics Art Examples

The following text reviews art installations referenced from the extensive overview of science artworks created by Wilson (2002). In order to reduce reviewer bias, works were chosen randomly from the topical areas of atomic- and molecular-level physics, physics in VR and information visualizations, science as information systems, nuclear and space physics, and the natural phenomena of time, electromagnetic spectra and auroras. A subset of the over 50 reviewed works is included here as selected examples.

Shawn Brixey – Eon

Shawn Brixey (2002) created the interactive installation *Eon*, an artwork that combines physics and advanced computing, to implement a sonoluminescence experiment within a museum setting. The installation is locally controllable as well as connected to the Internet to allow users to send elec-

tronic messages to a sonoluminescence device (see figure 5.1). The resulting light can be observed on screens and via the Internet as well as explored audibly through a sonification. The work extends the artist's research in the fields of telepresence and tele-epistemology. The work raises the question of whether natural phenomena, in this case the discrete interactions of matter and energy, are more believable than the sophisticated digital media technology tools used to create and sustain it.



(a) Installation diagram; image from (Brixey 2003)

(b) Rendering of sonoluminescence device; image from (Tribeca Film Institute 2003)

Figure 5.1: Interactive installation *Eon* by Shawn Brixey

The physics of sonoluminescence is an active area of research and not yet fully understood. This fact is highlighted through the creation of an interactive experiment which entices the observer to assume the role of a scientist and participate in the research of this phenomenon. Due to the technologies that have been used (e-mail, streaming video), and the online documentation which includes a computer-rendered animation of the "video-microscopic system and sonoluminescence cavitation chamber assembly," (DXARTS 2010) the resulting interaction has a distinct game-like aesthetic which helps to engage the audience. However, a certain seriousness regarding the experiment is created for both the local and remote user of the installation, through the

incorporation of the "enigmatic light-source" produced by a real sonoluminescence device.

John Duncan – The Crackling

The Crackling is an audio CD production composed from digitally edited segments of recordings made by the artists on location at the Stanford Linear Accelerator (SLAC) (Duncan & Springer 1996). A sonification of actual SLAC datasets and measurements was blended with ambient recordings from the accelerator itself. The production forms an artistic inquiry "into the nature of humanity's view of its place in the cosmos" but also provides a sonified record of one of the largest physics experiments created to date.

While the artwork presents a unique representation of physical reality, its focus is a critical examination of the metaphoric "cathedral" of science, which the SLAC structure provides, rather than a scientific discourse. The written documentation contains details of the instrument such as its dimensions and descriptions of experimental components or accurate "buzz" frequencies (120Hz). The artist, however, entitles the work *Necropolis*, to highlight the social context of "big science" and the fact that physics is "using forces and processes that are hostile or lethal to human life, yet are entirely human-created." Still, in the accompanying text, the listener is encouraged to treat the work as a device that metaphorically illustrates nature.

> The electron is understood as a metaphor for the process of life: isolated, compelled by a system that uses the electron's own energy to force it into a path that leads at a constantly increasing pace to certain destruction – to a point of certain change, of complete resolution and the beginning of a new process. (Duncan 2009)

Tim Otto Roth – I see what I see not

The non-interactive[4] installation *I see what I see not* by Roth (2003) presents real scientific data such as optical astronomical measurements (in the 2003/04 display) or particle-physics visualizations (in the 2005/06 display) as a media sculpture. The multimedia-architecture consists of a house facade constructed as a 10x10 matrix with light- and color-controllable rectangles (see figure 5.2) which are driven by selected subsections of existing scientific imagery ("source data") and an associated website. Using this method, the artist creates an interface between art and science, exploring the edges of technical perception and thus realizes "a beautiful game about the autonomous extension of constructive art by the means of physics." (Graff 2003) Physical reality is implied in the installation through the source of the data that is used (Roth 2007).

Figure 5.2: The *Internet Art Facade* displaying live KASCADE cosmic particle shower data (Roth 2004)

[4]There exists actually a browser based interface, but when in "science-mode," the facade is non-interactive.

The artwork chooses to use the *raw* data stream of science experiments, rather than simplifying and popularizing the information, and the documentation of the installation points to a key issue that visualizations of physics data face: lack of user knowledge. Roth states that "without the corresponding background knowledge, the phenomena remain invisible." For this reason, the artist includes detailed descriptions about the visualized source data with links to the various websites of the science experiments and other supplemental information (see *more* links in the "What you see (here)" section of the website). This approach allows the viewer to proactively learn about the physics and phenomena involved, enabling an informed re-experience of the artwork on subsequent visits. The artist thereby makes abstract and unfiltered science data accessible to a general audience by aesthetizing it, while remaining scientifically sound through the documentation and engagement of the cooperation partners in a "Wissenschaftsnetzwerk."[5]

D. Lsebrink & J. Sauter – Invisible Shape of Things Past

The artworks created under the title *Invisible Shape of Things Past* share a method that transforms film sequences into interactive virtual objects (see figure 5.3(a)), augmented architectural models or actual sculptures (see figure 5.3(b)), by mapping time into spatial coordinates (ART+COM 1995). The artists' primary motivation is to "manifest a counter position to the mania of the [then] widespread hyper-realism in computer graphics" and provide a tool for the "exploration of the representation of time in virtual space and the navigation through time in VR." (V2 1999) The filmed subject matter of the works is not related to physics.

Physics is introduced by the described artwork through the time-space

[5] *Wissenschaftsnetzwerk*=science network. The *Kunstfassade* website lists the following network partners: BELLE, STAR, KASCADE, MPIfR/DRAO, CDF/DO, BABAR, SOHO.

(a) Screen based application (1995) (b) Film based sculpture (2006)

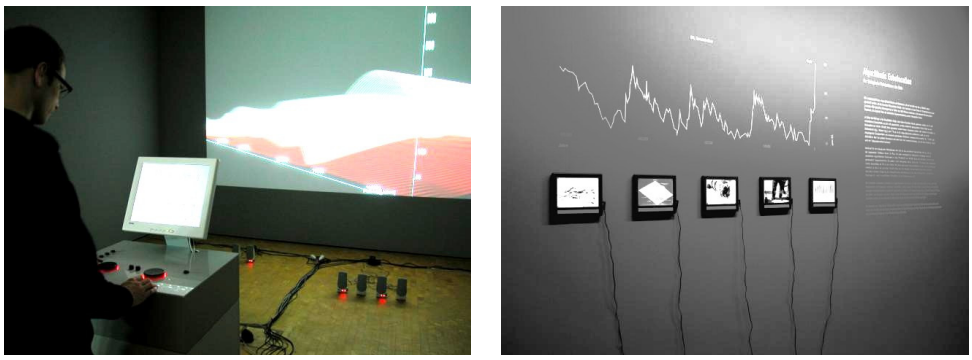
Figure 5.3: Parametric translations of movies into space in *Invisible Shape of Things Past*; images from (ART+COM 1995)

mapping method employed: the time of a recorded frame is being mapped to a spatial dimension in the virtual world or object. Computer games have been using similar discreet 2D-motion trail effects to accentuate the fast movement of characters or objects. The novel 3D implementation used in the artwork has a striking similarity to special relativity's concept of the *spacetime continuum* in which space and time are deemed reciprocal coordinates that are not constant, absolute or even separable. The approach to translate single frames consisting of pixels (picture elements) into spatial objects of voxels (volume elements) is a good method that can be adopted by GPEs in order to highlight the dimensional nature of space and time. It could even be used to illustrate abstract descriptions of nature, such as the *time reversal invariance* of some quantum field theories like the CPT theorem.[6]

[6]The *CPT Theorem*, if true, would require that all force laws are unchanged (invariant) on being subjected to the combined operations of particle-antiparticle interchange (charge conjugation C), reflection of the coordinate system through the origin (parity transformation P), and reversal of time (time reversal T). The experimental search for CPT violations is ongoing, thus making this a current topic in physics.

R. Guardans et.al. – Algorithmic Echolocation

The installation *Algorithmic Echolocation* presents a harmonic analysis of geophysical time-series data in the form of an interactive and dynamic computer graphics display (ZKM 2003*a*). One of the basic premises of the installation is the fact that large amounts of geophysical data which are being generated by science experiments and made available online, can be transformed into an interactive space. The artists suggest that the installation thereby becomes a new research tool. The system uses mathematical algorithms and physical data to create the audio-visual environments (see figure 5.4(a)) to be explored and *experienced* by the user in order to detect "traces which are not directly perceptible, and provide access to scientific models as well as abstract evaluation processes" of the physics involved (ZKM 2003*b*).



(a) Interactive interface (b) Documentation area

Figure 5.4: Visualization and sonification of scientific data in *Algorithmic Echolocation*; images from (ZKM 2003*b*)

The installation allows the user to control one or more features (dimensions) of the data. Single characteristics or combinations are being visualized and made audible through the algorithms of the artwork. Several dynamic patterns of the Earth's "global metabolism" are clearly identifiable in the

resulting multimedia display. The documentation ("Informationsblatt") accompanying the installation has scientific qualities, since it includes mathematical details about the wavelet-analysis used, describes the audio synthesis, references all data sources and points out the observable patterns of the Earth's climate which result from the periodicity of small regular fluctuations in the planet's motion around the sun. The subject matter is also presented with a reference to global warming (see figure 5.4(b)), enticing the viewer to seek correlations in the historical data with the current increase of greenhouse gas emissions in the atmosphere. The additional relevance created by this fact highlights the opportunity for educating the public through such works. The approach introduces explorative science by transforming data into multi-modal sensory information.

5.4.3 Principles from Physics Art

Based on the above examples, the following additional design principles for GPEs can be described:

P26 GPEs can substantiate some "seriousness" into game-like interaction and question the nature of scientific truth by "blending" reality into the virtual through the introduction of experimentally derived content, telepresence or physical devices.

P27 GPEs should attempt to expand the sensory output of games to non-visual media such as sound or physical objects such as sculptures or architecture.

P28 GPEs should allow the user to freely explore the dimensional and interchangeable nature of space and time (when applicable).

I have also reviewed other artworks[7] that employ the same principles. *Molecular Visualization* by Bettina Brendel (1994) is an example where physical reality is highly abstracted, similar to the previously mentioned "reductive" approach (**P25**). *Firmament* by Zina Kaye & Mr. Snow (2001) creates an "experiment" to engage the user (**P13**), combined with a sonification of physics data (**P27**). Peter d'Agostino's *Traces* (Electronic-Arts-Intermix 1997*b*) exemplifies the validity of employing a narrative GPE (see section 5.7). *Data Portraits* by (art)n (2006) has the goal to "place the most current issues of the arts and sciences into the public arena for social debate," with the result that "works have been viewed by millions of people" (**P17**) and thereby have served to educate (**P14**). *Time Concepts* by Sonia (Sheridan 2003) functions as a bridge between disjointed communities (**P17**) and features an exploration of space and time (**P28**). *Handsight* by Agnes Hegedus (1992) is a good example of how easy it is to extend standard game physics with new modes of visualization, as it creates a 3D projection mirroring the physical object (**P3**). *Particle Painter* by Tom Kemp (2004) innovates by using electrostatics (**P8**). However, the "charged particles" have no accurate scientific realization, and the artist provides no documentation of the actual physical laws used in the generator.

Several of the reviewed artworks do *not* seem suitable to advance game physics design but are listed for reference. James Acord's *Hanover Monument* implies physics tangentially through the installation's location, which is related to the history of nuclear research. In Gudrun Bielz's *Rays, an additional catastrophe*, the physics presented in the installation is limited to the documented theme of radioactivity and a single instrument exposing one physical property of the environment in a non-interactive way. Jay Lee and Bill Keay's *Suspended Window* uses animations of broken-up image squares that rebound back and forth with elastic properties in a simple dynamics

[7] Details in Appendix G.

simulation, and thus represents standard game physics. (SIGGRAPH 1999) Jane Marsching's *About Here and Later* attempts to create "an impression" on the audience by mixing scientific data with science fiction, circus acts, and architectural drawings, which is an overly broad approach for this analysis. *Déjà Vu of fresh water* by Gerstl & Keijser (2004) uses standard game physics in the rendering environment *Virtools* (Dassault Systèmes, 2005). *After Chernobyl* by Cornelia Hesse-Honegger (2001) has a theme with a very distant connection to physics through the fact that radiation might have caused the mutation effects in the documented subject matter. In *Electrum Tesla Coil* by Eric Orr (1998) the science of the discharge remains an "effect" for the viewer, similar to the "eye candy" in games.

As some of these examples illustrate, artists might be failing to address real physics in their work due to a lack of information or a shift in fundamental tangential approach to topics in science. I believe such works have the potential to mislead users and the general public, similar to an engagement with standard game physics. Section 5.5 will therefore illustrate the value new game physics might provide for artistic processes in the future.

5.4.4 Summary

It is my belief that the experimental approaches to physics that some media artists employ has great potential for the advancement of new game physics. Therefore, several works of media artists who share an interest in physics were also included in this investigation. The analysis of randomly selected science art was used to identify three additional principles for the design of GPEs (see section 5.4.3). This review also validated principles I had found previously, because some art installations support and share non-artistic GPE principles. In several cases, artists were found to be mostly focused on the cultural rather than physical phenomena, and this often meant the artistic

methodology involved physics only on a tangential level. Such works were found to be much less applicable to advance GPEs. Coincidentally, Shlain (1991, p. 25) has observed that artists "have continued to work in splendid isolation" from physicists, who are themselves "usually unaware of the artist's anticipatory images." Computer games using GPEs could well provide a new way to bridge the works of artists with the research of scientists, in particular since many artworks do exhibit a "delight of discovery," which is a common theme shared between the arts and the sciences. Artists and scientists *both* are able to be "uncomfortable with uncertainty" and want to learn through "hands-on interaction." (Blackawton et al. 2010, Grossman 2010)

5.5 Value for Artists

One of the aims of this thesis is to describe how game physics could add value to artistic practice and thereby contribute to the further understanding of our world. This section describes three artistic interpretations related to physics and then explains how new game physics could help these artists to represent the science in their work in other ways. New game physics may open up their interpretations, enhance their abilities to abstract complexity and extend their methods to express interpersonal significance.

The selected artworks comprise interactive works, or works that have the potential to become interactive. The artist, curator and theoretician Weibel (1992) describes the importance of interactivity in terms of art as an interface: "The world changes in relation to our interfaces with it. The limits of the world are the limits of our interface. We do not interact with the reality of the world, we do so with its interface." Artists have recognized the importance of computers in creating interfaces since the 1980s and have engaged in Human-computer Interaction (HCI) research themselves (Katre 2006), in particular through media art, which often explores the potentials of complexity through

interaction. As the users become participants in the artworks through their interactions, they assume a role that is very similar to that of a player in a computer game. I posit that the user of interactive media art is in fact a "gamer." Accordingly, GPEs are useful in this context.

5.5.1 Examples

The following examples cover the physics themes of time and space, true randomness and force fields. While there are many more physics elements that artists might be interested in, the topics should serve to illustrate the artistic value of GPEs. For each example from the arts, I assume the role of a consultant and proposes a game physics element which adds gamic interactions to deal with complexity, include content that increases the depth of the representation, or improve the accuracy levels to make the work more expressive. I propose that adding such attributes ultimately benefits the viewer or user "playing" with such works, and also constitutes a good value proposition for the artist.

Time and Space

Thomas Pynchon explores the larger concepts of time and space in his novel *Against the Day* by presenting his underlying vision in a highly complex structure – difficult to fix in space or time – so that the reader is constantly left in a state of uncertainty (The Complete Review 2009). Metaphorically, in the story, space becomes a *dream* and time is *defective*, as this quote illustrates:

> We make our journeys out there in the low light of the future, and return to the bourgeois day and its mass delusion of safety, to report on what we've seen. What are any of these utopian

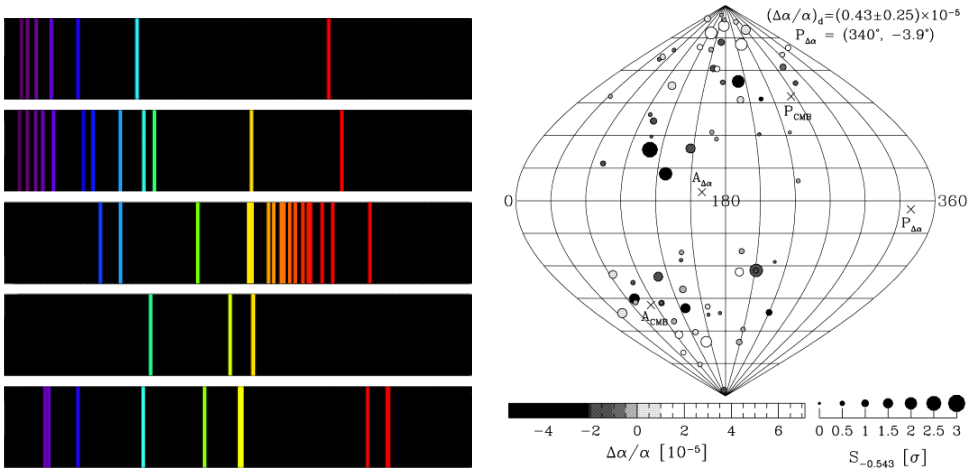
> dreams of ours but defective forms of time-travel?
> (Thomas Pynchon, *Against the Day*, 2006)

As a review of the book by satirist Palm (2006) reveals, Pynchon's meticulously researched text takes place in the "non-Euclidian world of Bernard Riemann, David Hilbert and Hermann Minkowski," three German mathematicians whose contributions directly enabled the development of relativity in physics, encompassing the two notable theories of Albert Einstein: special relativity and general relativity.

New game physics elements that explore non-Euclidian space could help readers of *Against the Day* to capture the existentialist experience of the novel and thereby assist them to accurately interpret the presented complexity. For example, the narrative could be augmented with a simulated experiment that allows the player to measure the fine-structure constant α.[8] But is the fine structure constant actually *constant*? A GPE can be designed where the player experiences α as a *non*-constant, or as Feynman (1985, p. 129) describes it, as "one of the greatest damn mysteries of physics: a magic number that comes to us with no understanding by man." The implementation of such a game element could for example present absorption spectra to the reader at any point in the story to interact with. The presented colorful spectrum of near-ultraviolet light would contain unique patterns of lines for different types of atoms (see figure 5.5(a)). In the envisioned game, the player could match these spectra, like a puzzle, to the different possibilities that arise from changing the value of α and map fictional places of the story onto a galactic map (see figure 5.5(b)), thus re-creating an actual experiment performed by Murphy et al. (2003). Physicists routinely assume that all constants are the same everywhere in space and time, despite that fact that this

[8] The *fine-structure constant* α is a fundamental physical constant introduced by Arnold Sommerfeld in 1916 to describe the coupling strength of the electromagnetic interaction. The numerical value of α is a dimensionless quantity and the same in all systems of units.

notion has not only been questioned, but essentially disproven by Barrow & Webb (2006). Murphy et al. provided evidence for a non-constant α through an experiment which compares spectral quasar observations with reference measurements in the laboratory.



(a) Sample absorption spectra of elements H, He, Ne, Na, and Hg (from top)

(b) Galactic distribution of $\Delta\alpha/\alpha$ as shown in (Murphy et al. 2003)

Figure 5.5: Experimental mapping of absorption spectra as evidence of a *non*-constant fine structure constant α

Thus, physicists may need to accept Pynchon's notion of uncertainty with regards to constants; whereas for readers of the novel, the gamic exploration of a non-universal physical constant that is indicative of the existence of extra dimensions in space adds to the depth of the story. With the described GPE, the artist has a tool to create not only an interactive novel, but also one that highlights the fact that those physical constants "are tantalizing mystery ... and they seem so prosaic that people tend to forget how unaccountable their values are." (Barrow & Webb 2006, p. 71)

True Randomness

Artist and researcher Rev. Luke Murphy (2008) has identified three main models of randomness as part of the artistic process: suggestion, inspiration and subversion. These models represent common strategies to circumvent our normal controls and frames of reference and can be illustrated by several historical examples. Leonardo da Vinci (1452–1519) already suggested staring at a dirty stained wall in order to free the imagination. Painter Piero de Cosimo (1462–1521) and later playwright and naturalist August Strindberg (1849–1912) methodically observed random patterns in order to discover new forms. In the art of Dadaism and Surrealism, the unconscious is aligned with the random to allow it "to reveal itself." For example, Tristian Tzara (1896–1963) wrote a poem by drawing words from a hat – an idea so radical that it got him expelled from the surrealist group. Later, the inclusion of randomness became integral to system aesthetics, in which the random number generator is a stand-in for nature, as exemplified in Marcel Duchamp's work "Three Standard Stoppages" (1913–1914). Later, in Hans Haacke's "Condensation Cube" (1963) the extended physical processes generated within the work are deemed to operate randomly in relative independence from the viewing subject. Compositions of aleatoric music, such as John Cage's *Music of Changes* (1951) are pieces that are conceived largely through random procedures, involving physical elements of chance like throws of dice or coins to create "indeterminacies of composition or performance." (Simms 1986, p. 357)

From the advent of digital media art in 1970 onwards, one can observe the ubiquitous use of PRNGs, which are mere simulations of natural stochastic behaviors. Such use is strangely at odds with the fact that in computer-based art, artists often use randomness as a source of fascination in an attempt to capture nature's *unconscious* (Jones 1989). For example, digital

and algorithmic compositions often rely on the simulated randomness of a PRNG, disregarding the physical roots of aleatoric music. In section 5.9.1, I therefore describes a new GPE which attempts to overcome this limitation by collecting and distributing physical entropy derived from Geiger counter measurements. Digital media art can create unique value by integrating such Hardware Random Number Generator (HRNG) data, because of its connection to natural processes and historical precedence.

An approach similar to the described GPE was implemented by computer scientist Mads Haahr (2008), who operates a public website that offers *true* random numbers derived from atmospheric noise. Haahr published several testimonials from artists on his site (see `http://www.random.org/testimonials/arts`), which illustrate quite well the unique value such a service can offer to the art community. Curator G. Freeman employed *random.org's* HRNG to assemble recordings of John Cage's Number Pieces *truthfully* (Freeman, 2007). Musicians such as J. Wolfe, W. Orzo, J. Gaudasinski and others use the HRNG in their compositions and tone generators and report that "results have been very *promising*" (Gaudasinski, 2007). Writer H. Witham copied Tzara's approach, as she writes a story and lets the HRNG pick out "the next two cards" from her collection of notes to define her *personal* narrative. As is visible from the posted comments, artists found the use of a physical random number source appealing because it created a "subliminal depth" or simply represented a "wonderful and useful tool" (H. Cowherd, 2000).

Force Fields

The artists group Knowbotic Research (KRcF) explored process-based art in a project series entitled *IO_dencies* in the 1990s. Their works employed interfaces and online communication tools that allow participants to interact

and continuously transform a shared knowledge environment. These artworks are "exemplary for an artistic engagement with technologies in which the *machinic* dimensions of a system including technology and human actors, are deliberately explored, rather than being taken for granted, or ignored." (Broeckmann 2005) The *IO_Dencies - Sao Paulo* system created a specialized multi-media database in the context of urban development with an emphasis on collaborative work, planning and information retrieval. The system included a visualization and force-feedback interface driven by a force field: the position of each keyword in the database is assigned a local field pattern and the algorithm produces a two-dimensional map of force vectors by accumulating all local fields. To make the visualization of clustered information obvious, a cloud-like visual style was implemented where particles flow inside the simulated force field (Pettifer 1999).

The force-field algorithm was originally designed and implemented me and is used to facilitate the visualization and user interface for the *IO_dencies* installation (Schiffler & Schwabe 1998). The algorithm maps meta-data associated with each entry (keywords, number of clicks, number and direction of relations) to the variables of a force point (type, strength, range and direction). A finite number of predefined field types are defined using mathematical equations which describe a 2D force vector $\vec{F} = (f_x, f_y)$ that a particle at position $\vec{P} = (dx, dy)$ away from a force point at distance r would experience.[9] Examples of such equations used in the installation are:

$$f_x = c_{scale} 1.2195 \cos(10dy + \frac{\pi}{2}) \tag{5.1}$$

$$f_y = c_{scale} 1.1111 \tag{5.2}$$

or

$$f_x = c_{scale} 1.1904 \cos(8(dx^2 + dy^2)) \tag{5.3}$$

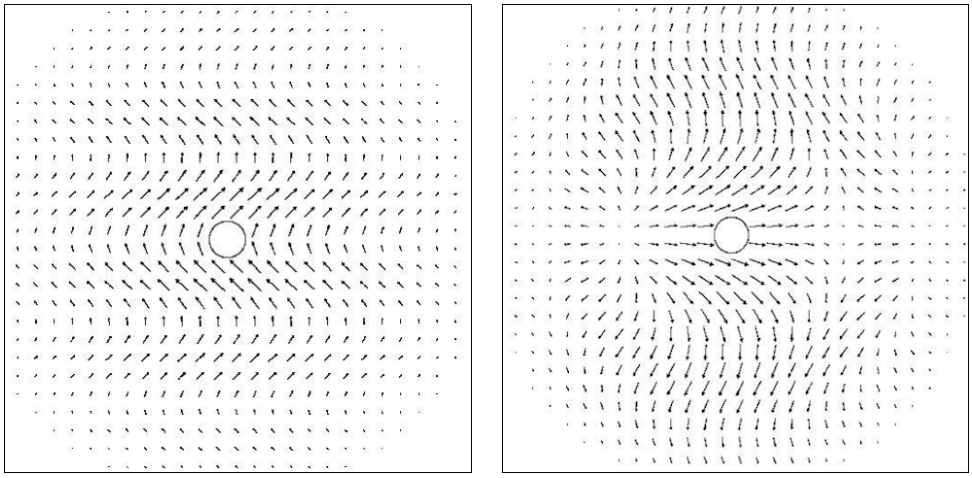
[9]Distance r is normalized to the range [0,1] with respect to the field's maximum size.

$$f_y = c_{scale} 16.667 \frac{dy}{(dx^2 + dy^2 + 4)} \tag{5.4}$$

where

$$c_{scale} = 1 - r \tag{5.5}$$

The public art installation used an interactive particle-flow visualization, but the resulting fields may be visualized as vector diagrams for illustrative purposes (see figure 5.6).



(a) Field of equations 5.1 and 5.1 (b) Field of equations 5.3 and 5.4

Figure 5.6: Sample force-field types for force points associated with *IO_Dencies* multi-media database entries

Although the described implementation strongly suggests that physical laws were used to create these *IO_dencies* force fields, I can attest that this was not the case. The design of the fields was done in an ad-hoc fashion, guided by aesthetic rather than scientific principles in order to maximize the visual impact of the resulting particle flow. While the mapping of database meta-data did correlate user activity with field strength, for example, the actual presentation of the installation did not provide any further details on

the nature or origin of the force fields.

A new game physics element which represents naturally occurring forces may provide dynamically rich fields while also being physically correct. It is easy to find usable vector fields in many areas of physics, such as the applications of Maxwell's equations in electrostatics or electromagnetism, the velocity of a moving fluid (or gas), the gravitational fields of massive objects or even astrophysical magnetohydrodynamics (MHD). If physically accurate field simulations were employed, the artists would be able to map the contextual meta-data (i.e., properties defined in the *IO_dencies* database related to urbanism) to actual physical properties (i.e., charge, spin, pressure, or mass). This gives the artists a much more expressive opportunity over the previous simplistic use of algorithmic parameters, and could mean that their vision is represented much more accurately to the viewer. Hence, this game physics element extends their artistic outcome. Physical models may also allow the artists to explore novel forms of introspection and interaction with such fields. Plasma theory describes, for example, the properties of MHD waves present in astrophysical plasmas (i.e., the corona of the Sun) with vector fields, which can be simulated numerically via existing software used by the physicists. The resulting turbulences may be sonified rather than visualized, which adds a new mode of interaction.

5.5.2 Summary

I sketched some possible game physics elements that could provide artists with a set of added values such as methods to deal with complexity. Such content adds depth and representation which aid in the expressiveness of their works. In each case the use of game physics does not modify the artists original intent, but rather it could actually augment it. The examples also show that within the context of transdisciplinary teams, art can act as a

catalyst to bring science to the public. Furthermore, if artists implemented their installations with the rigor and depth required for new game physics elements, it would open up their works to new audiences such as game developers and scientists. Why would artists want to widen their audiences today? In relation to the sciences, media artist Jill Scott (2010) argues that artists should embrace the "art/sci-margin ... to re-share controversy and discuss action." She posits that this will happen "only if artists move beyond the *me* generation and the post-modern dilemma, into a role where art can again become a larger part of life." Artists should also get more in touch with game developers, because "digital media are slowly but inexorably transforming aesthetics and our tastes" through game aesthetics (Quaranta 2006). As media theorist Manovich (2001) points out in his *Info-Aesthetics* manifesto: "The challenge before us is to figure out how to employ these tools to create new art." But could computer games be used in such a transdisciplinary context? I posit that a practical approach – implementing and using actual GPEs – can provide at least some answers to this question.

5.6 Elements: Physics in Game Mechanics

Since physics is rich in rules and games are often about the negotiation of rules, it makes sense to seek out laws in physics that can be appropriated for computer games and attempt to implement new game physics elements from them. When rules are applied to games, the resulting elements create new game mechanics. One of the challenges for such game mechanics is to attain both entertainment and science goals.

It is relatively easy to find physical laws that have not been used in games. One may narrow the search to laws involving spatial properties of nature. Negotiating space is a prime function in almost all computer games because it is so easy to create and represent actionable space in a digital environment.

Aspects of physics that are intimately connected to the concepts of time and space include modern physics concepts such as relativity or quantum tunneling. The following GPE implementation will use laws from relativity theory to extend gamic concepts of space and time.

5.6.1 Relativity Theory and Game Time

The representation of time is fundamental in a computer game, as it provides the means (creating flow) and the end (relative sense of time). How could one relate this *game time* to physics? In 1905, Albert Einstein proposed the theory of Special Relativity (SR) which provided the physical basis for measurements in inertial frames of reference.[10] According to SR, these frames are related by Lorentz transformations, which are laws describing how measurements of space and time can be converted into each other's frames of reference. These transformations have consequences, including counter-intuitive ones, related to time. Ever since the publication these theories, many have been curious about their effect on simultaneity, which seem to be contradicting the classical notion that the duration of a time interval between two events is equal for all observers (Resnick 1968, pp. 62-63). The following GPE description proposes a way to utilize this aspect in games and is applicable to games that place game objects into contexts of fast motion such as space travel.

The Dilation of Time

Due to the fact that the speed of light has an upper limit, the law of special relativity states that when two observers move relative to each other, i.e., there exists a non-zero relative velocity between them, the observed time in

[10] An inertial frame of reference is defined as one in which all laws of physics take on their simplest form.

one observer's frame of reference is different from that of *any* other frames of reference. The point of view of each observer will generally be that the other observer's clock has slowed its rate, hence the term "dilation."[11]

One can calculate time dilation using a formula which depends on the speed of the object. A clock measures a time interval $\Delta t'$ in a system moving with speed v relative to a stationary observer measuring time Δt. The ratio of these time intervals – an indication of how much a clock moving at speed v seems to slow from the stationary observer's point of view – is given by the Lorentz factor γ:[12]

$$\gamma = \frac{\Delta t'}{\Delta t} = \frac{1}{\sqrt{1 - (v/c)^2}} \tag{5.6}$$

Speeds that can be achieved by macroscopic objects using available technology, even considering space travel, are not great enough to produce easily detectable time dilation effects. However, time dilation has been experimentally verified;[13] and some modern applications based on precision timing, such as the Global Position System (GPS), must take dilation corrections into account to function correctly (Ashby 2003).

Time Dilation as Game Element

Many computer games with a science fiction theme assume that technological challenges for space travel will have been solved in the future and so incorporate travel between planets, solar systems or galaxies as a primary game

[11] A similar effect due to gravitation is described in *general relativity* which states that clocks at lower potentials in a gravitational field are found to be running slower.

[12] c denotes the speed of light; c=299,792,458 m/sec

[13] A particularly simple experiment was conducted by Rossi and Hall (1941), who compared the population of cosmic-ray-produced muons at the top of a mountain to that observed at sea level. The difference in their measurements can be easily explained through the time dilation effect: the fast moving muons were decaying much slower than if they were at rest with respect to the experimenters.

element of space negotiation. However, I am not aware of any game that considers any relativistic effects; thus games must rely on a simplification of physics required to allow for travel across such distances, neglecting the time dilation phenomenon which becomes dramatic as objects move near the speed of light.

Since games frequently use a first-person perspective, the player's frame of reference is often stationary. In this situation a clock representing game time (i.e., the date shown in a heads-up display overlay on the screen) is fixed from the players point of view. However, other game objects move relative to the player's frame of reference, which causes their clocks to be subject to time dilation. Since time dilation affects the rate at which time passes, the total discrepancy between the stationary clock (player) and moving clocks (game objects) increases constantly, thus quickly rendering the classical notion of a constant, uniform time for all game objects inaccurate.

The proposed GPE would introduce the simulation of time dilation for all moving objects in game space as follows.

1. The player's time is tracked as T_{player} and all n game objects in game space are associated with independent object clocks $T_{object}(n)$.
2. Initially, all clocks are synchronized: $T_{object}(n) \Leftarrow T_{player}$.
3. During the game loop, common game time advances in intervals Δt and player time is updated *without* dilation: $T_{player} \Leftarrow T_{player} + \Delta t$.
4. An algorithm determines the speed of all game objects relative to the player's coordinates and applies equation 5.6 to obtain Lorentz factors $\gamma_{object}(n)$ for each game object.
5. All object clocks are advanced using the dilated interval $\Delta t'$ as follows: $T_{object}(n) \Leftarrow T_{object}(n) + \gamma_{object}(n) \cdot \Delta t$.

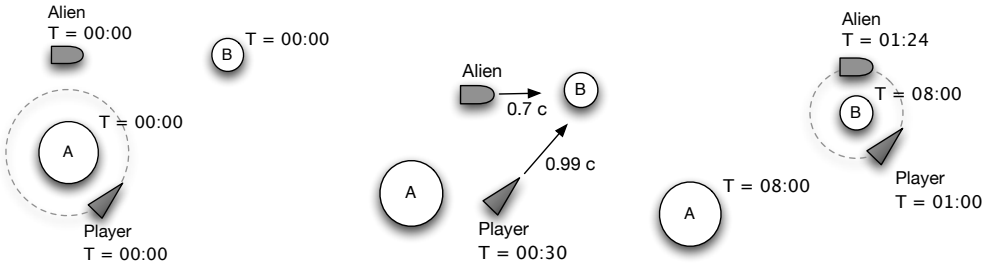
The gameplay logic now has access to a common game time from the perspective of the player as well as dilated game times associated with each object. The availability of independent clocks for each game object can be used to create new gameplay challenges by adding rules which require the player to "negotiate time" on top of the traditional space negotiation rules. As an example, for each day on a simulated space ship traveling at 99.9999% of the speed of light away from a planet,[14] almost two years would seem to pass on the planet for every day of the ship's travel (Walker 2010*b*). The element is even applicable for turn-based games, as long as the relative speeds can be calculated and are in ranges that produce measurable dilation effects ($speed > 0.1c$). Since this GPE is based on special relativity which states that no object can move faster than the speed of light c, games using this GPE should not suggest the availability of non-physical faster-than-light (FTL) travel which is commonly used in movies and literature.

Example of a Play Scenario

The following scenario will illustrate how the inclusion of a time dilation factor during space travel simulations would affect the gameplay dynamics of a hypothetical "space colonization" game. Figure 5.7(a) shows a possible gamespace containing a planet (A), a moon (B), a game object (Alien) and the player's spacecraft (Player).

As the game starts, the player leaves the orbit of the planet to initiate a trip at about 99% light speed towards the moon to intercept the alien ship. Assuming this trip takes an hour, 5.7(b) shows the position and speeds of all objects halfway into the flight. After 1 hour, the player arrives and the spacecraft enters into an orbit around the moon. As figure 5.7(c) indicates, the player finds that all object clocks are out of sync due to the time dilation

[14]This GPE does not consider the technical feasibility nor physical reality of a space ship capable of moving at the suggested speed of near c.



(a) Launch (b) Flight (c) Arrival

Figure 5.7: Time dilation scenario for player rocket flying from planet A to moon B intercepted by an alien ship

effect. From the player's first-person perspective, 8 hours have apparently passed on the moon base. Similarly the clocks on the alien ship recorded 1 hour and 24 minutes. These different times are now available for the game designer to produce enriching variations to the gameplay. For example, the dilated time could be used to impose economic or technological implications on the moon base or the alien ship, which create strategic advantages or disadvantages for the player (e.g., radioactive components have decayed, resources have been depleted, populations have evolved).

Applicable GPE Principles

This element – simulating time dilation in space travel – introduces several GPE principles. A new field of physics is applied to computer games (**P8**) through the use of special relativity. It clearly displays the effects of a departure from the common Newtonian worldview (**P7**) through the time dilation effect. The introduction of a unique game time for all moving objects adds complexity to the game (**P18**) and intellectualizes a traditional game genre (**P23**) with a simple rule that creates the fairly abstract behavior of associating different clocks to all objects.

The player can be exposed to the mathematics and derivation of the Lorentz transform (**P4**) by including the formulas in the documentation. The game designer may choose to ignore the technical feasibility of near-speed-of-light space travel to keep this element educationally accessible to a broader audience (**P14**). Another choice for a game designer would be to model the physical implications of near c speeds, such as the *aberration of light* (Walker 2010*a*), using advanced computer graphics (**P15**). If the game avoids the availability of faster-than-light (FTL) travel (**P11**), the player is forced to explore a space-time continuum (**P28**) by trading faster travel for greater time dilations. Furthermore, the element is applicable to multi-player implementations, placing its mental challenge into a competitive context (**P19**) to aid acceptance by the players.

5.6.2 Pendulum "Flip a coin" Generator

As section 5.9.1 demonstrates, many games involve random numbers to simulate natural behavior and expand the games state space. However, often only a simple random binary choice such as a "coin flip" is needed. For example, the game may want to determine which player starts or whose team he/she is on. The unpredictable dynamics of pendulum systems (see section 5.8.1) can be used to construct a GPE that generates a *random bit* interactively for such purposes.

A Choice from Chaotic Motion

Simple physical systems such as pendulums can be simulated in most current game engines and may be configured so they exhibit highly unpredictable motion. The *Forced Spherical Pendulum* is such a physical system. It is composed of a weight suspended from a pivot, swinging freely in three dimensions, where the pivot point is "forced" to move horizontally via oscillatory motions.

Figure 5.8: Fractal of colored attraction basins in the phase space of Hubbard's Forced Damped Pendulum (Béky 2009)

Tritton (1993) demonstrates that this dynamic system exhibits either ordered or chaotic motion depending on how the pivot is perturbed. In the spherical pendulum system, small driving frequencies establish a regular and nearly circular motion. However, even this regular motion is not completely predictable. The direction of the final motion (clockwise or counterclockwise) is random due to an extreme dependence on the initial conditions, which must contain some non-deterministic components owing to their physical makeup. So the basis of this GPE is the fact that any variability in the setup, such as player input to the initial conditions, is amplified through the chaotic properties and will produce a random simulation state over time.

The future position of these pendulums is especially unpredictable when a pendulum *bob* – the weight at the lower end of a pendulum – is launched from a starting position that leads to chaos. Fractals generated from the pendulum motion can be used during the design process to locate zones leading to chaotic motion (see also 5.8.1). For example, the similar *Damped Forced Pendulum* was described by Hubbard (1999) and visually analyzed by Béky (2009) as shown in figure 5.8. If such visualizations were shown in a game, they would introduce a unique aesthetic element to this GPE and

illustrate the fact that *simple* mechanical systems can create very *complex* behaviors. That chaotic motions of pendulums are interesting to watch for a player is exemplified by the commercial success of a magnetic pendulum toy, the *R.O.M.P. - Randomly Oscillating Magnetic Pendulum* (Hog Wild Toys, USA). The product description reads as follows: "Designed to illustrate the chaotic and random forces that effect us all, ROMP is also just plain fun. ... Users are limited only by their own imagination. ... ROMP's dramatic movements will keep you awake." Therefore a key part of the GPE implementation concerns its visualization, which should enhance the aesthetic impact of the motion, for example by drawing the trajectories of the pendulum orbits.

The proposed GPE would introduce a visualized random-choice generator as follows.

1. A suitable non-linear pendulum system (i.e., magnetic pendulum, forced damped pendulum) is chosen and its numerical model derived.
2. The simulation is implemented using an existing game physics engine or a custom algorithm with a suitable numerical integration scheme.
3. A fractal map is generated once from the simulation, in order to determine stable areas that cannot be used as starting positions.
4. A graphical interface is implemented that allows the user to modify the initial positions and simulation parameters of the pendulum.
5. The player-initiated simulation is run for a minimum amount of time (or until stopped by the user), during which the motion of the pendulum is visualized.[15]
6. Once the chaotic system has evolved sufficiently (as guaranteed by the minimum runtime requirement of step 5), the physical state of the

[15]The fractal map generated in step 3 could be reused in this display to enhance the aesthetics of the simulation.

simulation (i.e., handedness of the orbit or position in phase space) can be used to determine a single random bit representing the “heads” or ”tails” of a coin flip, thus generating a random choice.

Applicable GPE Principles

The described choice generator uses a physical simulation to make a binary decision in the game (**P18**, **P22**). The visualization adds a unique and abstract aesthetic component (**P25**) which is entirely physics-based. During the initial setup by the player and during the simulation run, the pendulum state may be displayed (**P1**), allowing for in-game experiments (**P13**) with the physical system. The simulation model may be arbitrarily sophisticated[16] to allow the player to choose additional parameters (**P9**) besides the initial bob position. The mathematics of the pendulum should be described in the documentation of the game (**P4**). Video footage of an actual chaotic pendulum may be blended into the game screens, or instructions of how to build a pendulum device could be provided to the player as part of the game's documentation (**P26**).

5.7 Elements: Physics as Game Story

The history of discoveries in physics provides novel narratives. I propose that these stories can be appropriated into games, thus forming new game physics elements based on narrative structures. The narration can deal with the fundamental questions that are raised during the process of discovery. In addition to new story lines, this approach would also provide suitable semiotic domains for physics that could then be combined with other GPEs to enhance their learning effect or immersion. For example, non-narrative

[16]Most models documented in the literature use an idealized pendulum which does not take small effects from friction, air, gravity variations, and other factors into account.

GPEs that create physics-based visual game aesthetics may be too abstract for players, unless combined with a suitable narrative physics element.

5.7.1 The Birth Cry of Atoms

The element described in this section will draw from a text of the same title by Capri (2007, pp. 5–14) about the discovery of cosmic rays. His anecdotal history of physics is written in a prosaic format with a clear timeline and many colorful characters, as well as biographical notes and actual quotes to illustrate the story. This format makes the text an excellent resource to create a compelling narrative game physics element. This section describes a high-level GPE design as a narrative that could be converted into a game.

Implementing Game Narratives

Narrative game physics elements may be implemented as a graphical *adventure game*, which is a style of gameplay pioneered by the 1970s computer game *Adventure* (W. Crowther/D. Woods, 1976), since it is the game genre most closely related to other narrative-based media. The player generally assumes the role of protagonist in an interactive story driven by exploration and puzzle-solving to complete the assigned quest (Ernest Adams 2006).

Adventure games are commonly realized as a collection of "game assets" (data files) driving a generic game engine. This allows the game mechanics created by the engine to be shared between different stories (games), which helps users by unifying the game interface and makes content authoring more efficient. Well-known adventure game engines include, for example, the commercial *Script Creation Utility for Maniac Mansion*[17] (SCUMM) or the open

[17]Lucasfilm Games/LucasArts, 1987-1998.

source *Adventure Game Studio*[18] (AGS). When game engines are used, the game designer starts by defining a *narrative* (game story), which is the basis for all "game assets" required to implement the game. Asset data that needs to be produced includes rooms (background images, activity edges, accessible areas, walk-behind areas), interactions (game progression logic, hotspot actions, walk-to points), characters (names, animations), objects (inventory, placement, interaction rules), conversations (dialog trees), visuals (color palette, cursors and fonts) and audio (music, sound and speech). These assets are then combined to represent the plot of the narrative as an interactive story; the data set is added to the game engine; and both are finally converted into an executable format for distribution.

The following text will describe a physics-based game story, a narrative GPE, which could be used to define game assets and implement an adventure game.

Story Summary: The Discovery of Cosmic Rays

The setting is the early twentieth century, and the goal of the quest is to prove the existence of cosmic rays and get the Nobel Prize award in physics. The protagonist, controlled by the player, is a physicist who collaborates with the various scientists involved in the discovery of cosmic radiation. The story begins in 1912 with a balloon flight of the Austrian physicist V. F. Hess, who is measuring electroscope discharges at high altitudes. The player joins the balloon flight and participates in the experiment by assembling the equipment and taking measurements. As the balloon rises, the findings are that discharges are initially slowing down, but above 600 meters the trend reverses and at 5000 meters the electroscope discharges almost four times as fast as on the ground. This discovery is attributed to "Ultragam-

[18]See `http://www.adventuregamestudio.co.uk/`

mastrahlen"[19] and the player joins physicist R. A. Millikan, who proclaims incorrectly that these measurements are caused by proton-fusion reactions, "the birth cry of atoms." The player then follows J. R. Oppenheimer, who suggests also incorrectly that such cosmic ray primaries are uncharged particles. The player will learn that by measuring the intensity of cosmic rays closer to the poles, one may detect a *latitude effect* and establish that cosmic rays are in fact charged particles, thus refuting Oppenheimer's idea. After working with young postdoctoral fellow H. V. Neher to assemble an accurate and robust quartz electroscope, an instrument with sufficient accuracy needed to measure the latitude effect, the player continues to travel with physicist A. H. Compton on his 80,000-km journey across five continents, taking measurements. Meanwhile side-plots develop: measurements of cosmic rays and radium are taken at the top and bottom of the Grand Canyon, using mules to travel the terrain; due to a lack of equipment in India, a temporary electroscope needs to be constructed from the bowl of a *hookah* (a water-pipe); during the trip through the Himalaya mountains, Compton's wife Betty and lab assistant N. Ahmad start to educate Muslim girls about science. Once this part of the quest is complete, the player may confirm the latitude effect with the collected data, only to be disappointed again, since in 1933 the latitude effect is correctly attributed to the "solar wind" which consists of protons ejected from the sun, rather than cosmic rays. The player continues the research into cosmic rays and joins H. Geiger and W. Müller to invent the *Geiger-Müller counter*, a device that allows one to detect individual subatomic particles. With this new instrument and these colleagues, the player constructs an experimental setup: two counters are placed above each other with a 4-cm-thick gold bar between them. This setup allows the player to conduct an experiment which establishes that cosmic rays are indeed charged particles, after researching in the lab library that photons could not have penetrated the gold. To complete the quest, the player to-

[19] *Ultragammastrahlen* = ultra-hard gamma rays, a photon

gether with physicist C. D. Anderson must finally use a cloud chamber to photograph cosmic-ray tracks under the influence of a 300,000-Gauss magnetic field. With this new device, the positron and "heavy electron" – the muon – can be detected in the cosmic radiation. The player is then joined by Hess and Anderson in Sweden to be awarded a Nobel Prize in physics in 1936 "for the discovery of cosmic radiation," which completes the game.

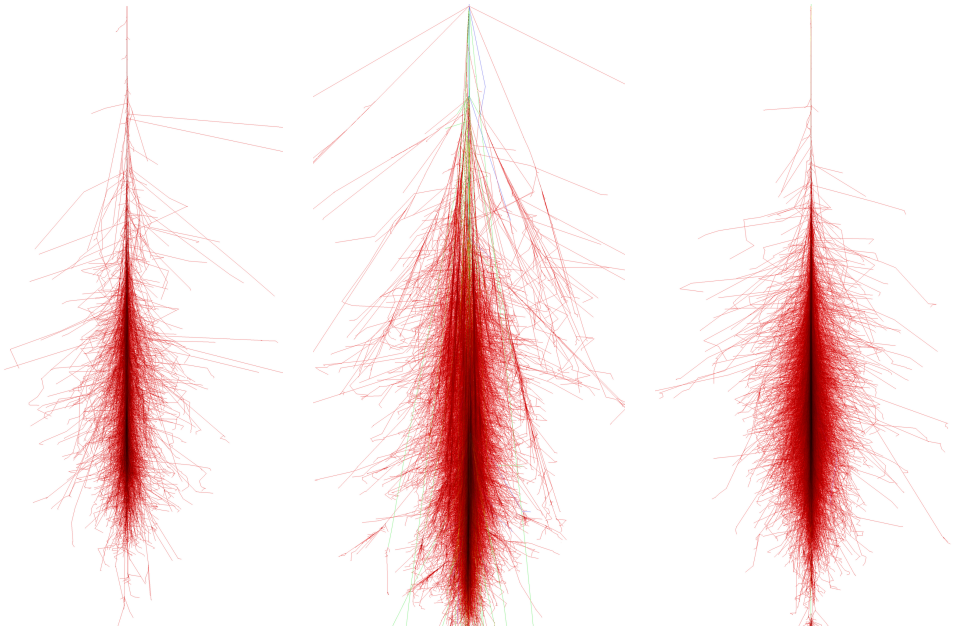
Applicable GPE Principles

The story covers a field of physics not commonly found in games (**P8**) by choosing "particle physics" as its topic. The subject matter, combined with the implementation as an adventure game, a declining game genre, has the potential (**P12**) to be discovered by new generations of casual players. While MMORPGs have partially supplanted the adventure game genre in the marketplace, the genre is ideal for mobile platforms (**P16**) due to its lower hardware resource requirements. Furthermore, many mobile devices feature a touch interface and contain a global positioning device, which provides multimodal interactivity (**P27**) and may improve immersion for the player.

As the story outline indicates, the game logic should implement several "experiments" (**P1**) that the player needs to perform interactively (**P13**) to advance gameplay. To aid the player, the game can include the mathematical background (**P4**) and historical documents (**P10**) of the experimental setup as part of the player's "inventory." A point-scoring system for successful experiments, and the game's goal of winning the well-known Nobel prize, complement and balance the mental challenge to understand physics with competitive elements (**P19**).

If a realistic (non-cartoon) style is chosen for the visuals of the game, it should be designed to support the player's agency as "scientist" (**P21**). Additionally, the linear game flow can be interrupted (**P22**) at opportune

times, such as when the player meets a new physicist, by introducing the aesthetically rich images generated from simulations of the CORSIKA (COsmic Ray SImulations for KAscade) air shower simulation program (see figure 5.9). These "cut scenes" could be interactive and provide a moment of "free play" (**P20**), allowing the player to explore the physical processes visible in the images such as Bremsstrahlung, Pair production, deflection of particles in the Earth's magnetic field or Compton scattering.



(a) Photon, $10^{11}eV$ (b) Proton, $10^{12}eV$ (c) Muon, $10^{15}eV$

Figure 5.9: Traces of atmospheric particle showers generated using the CORSIKA simulation software (Schmidt 2005)

5.8 Elements: Game Aesthetics from Physics

Representations of scientific simulation results are usually visualized (and less often sonified). Could new game physics elements be based on such

aesthetics? Because scientific visualizations often show potential to be perceived as something "which appeals to the senses," this section will explore approaches through which physics can influence the aesthetics of games.

GPEs developed in this section will attempt to utilize properties of physical systems to generate graphics that enhance the aesthetics of games. The visual beauty of *chaos* became mainstream when Mandelbrot (1977) published images of the iconic "Mandelbrot set" fractals in his book *The Fractal Geometry of Nature*. Physical system also exhibit "chaos" and many are very good candidates to create engaging visuals for games, as was described earlier (see section 5.6.2). These systems create an aesthetic result which is hard to replicate by other techniques, as they blend *both* regular and irregular forms in a unique way. For example, fractals have been used extensively in computer games for the generation of shapes and textures that resemble natural phenomena, such as clouds, mountains, or trees.[20] However, this usage of fractals is usually not physically motivated, or their implementation is not based on actual physical laws. This opens up an opportunity for new GPE designs.

5.8.1 My Avatar is Chaos

Many physical systems are non-linear and behave chaotically, and some can be used to generate fractal images. This property is combined with the fact that current game consoles include a persistent representation of the player as an *avatar*, which is often represented as an image or humanoid 3D model. For example the *Xbox Live* system features a "gamercard" with a picture rendered from the player's customized 3D avatar (see figure 5.10(a)).

[20]Realistic representations of natural elements such as wood, marble, granite, metal or stone in games commonly use *procedural textures*, which are based on algorithms that use recursions, fractal noise and turbulence functions to simulate self-similarity and "randomness" found in nature.

This GPE proposes to generate avatar images using graphical renderings of chaotic physical systems, and thereby to introduce a new physics-based game aesthetic.

Gumowski-Mira's Strange Attractors

How can physical systems generate chaos that is related to an aesthetic experience? Many physical systems are described by deterministic equations, meaning that their future behavior is *in theory* fully determined by the initial conditions. One observes, however, that the system's evolution over time is not predictable due to an extreme sensitivity to those initial conditions. Even when random influences are ruled out, the slightest change in the starting condition will produce new, unique states over time. Systems that show this behavior are said to exhibit *deterministic chaos*. This behavior is found in a very wide range of natural phenomena such as the planetary weather, gravitational or magnetic fields of celestial bodies, neuronal activity, molecular vibrations and many others. Briggs (1992, p. 30) describes the aesthetics of such deterministic chaos as a "holistic harmony in which everything is understood to affect everything else." In his text, he shows that chaos brings out what artists seek to represent, which is "an aesthetic experience that involves a transformation which takes place in *both* the object and its observer." Since modern chaos theory delineates clearly the limitations of the old "reductionist" approach to physics, which separates object and observer in a "clockwork universe," the aesthetics of chaos is in fact a successful vehicle to bring together the two cultures of modern physics and art. The problem this GPE has to solve is to find methods through which these visually representable systems can be associated with a player's avatar.

The nuclear Physicists I. Gumowski and C. Mira discovered one such method. During their research at the European Organization for Nuclear

Research (CERN) center, they formulated equation 5.7 to calculate the trajectories of sub-atomic particles.

$$F(x) = \alpha x + \frac{2(1-\alpha)x^2}{1+x^2} \tag{5.7}$$

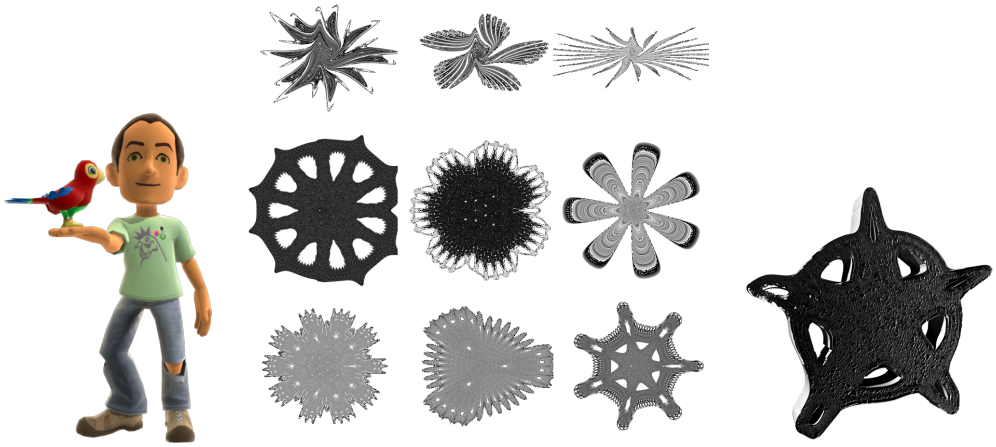
While visualizing the evolution of this system over time, they found that it leads to patterns that consist of complicated sets of points also called "strange attractors," which can be used to render images. The resulting *Gumowski-Mira Fractals* are beautiful in a subtle way, since the patterns have a striking similarity to forms present in the natural world such as citrus fruits, single-celled organisms or bird feathers. The proposed GPE would let the game players create such fractal images interactively, allowing them to choose an image from the infinite number of possible choices (see figure 5.10(b)) as their avatar representation.[21] This process is similar to the approach of artists such as Keith Peters and Tom Beddard, who have explored the aesthetics of these fractals in their works by exploring and selecting features they found interesting.[22] Parity with commercial avatar representations can be achieved, if the fractal image is post-processed into a 3D representation using vectorization and rendering techniques such as extrusion (see figure 5.10(c)).

Pendulum Dynamics and other Visions of Chaos

The fractals illustrated in figure 5.10(b) are based on just one method, which can be used to generate patterns from physical systems, but many others are available as well. In section 2.3.2, standard game physics was shown to be focused on object dynamics, thus capable of simulating a pendulum. Pendulums are used in clocks, which make them an exemplification of regularity,

[21] An application to demonstrate an interactive fractal selection is included in the Proof of Practise of this dissertation.

[22] See `http://butdoesitfloat.com/filter/Keith-Peters` for samples.



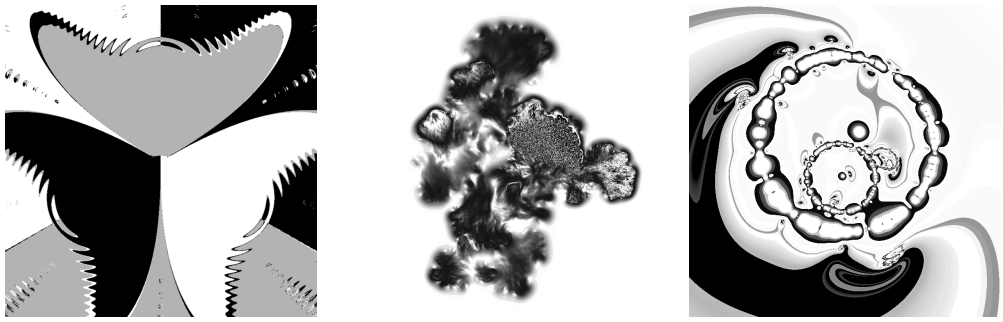
(a) Xbox Avatar (b) Selection of Gumowski-Mira Fractals (c) Physics Avatar

Figure 5.10: Player avatar based on a fractal generated with the physical Gumowski-Mira mapping

but they can still show deterministic chaos in various ways. This property is caused by the pendulums' fundamentally non-linear behavior. Accordingly, chaotic pendulums can be used in GPEs to create aestheticizing visualizations. For example, it is impossible to predict accurately the future position of a pendulum bob that is attracted to magnets below it.[23] When the bob of such a *Magnetic Pendulum* is released with sufficient deflection, the position after about 10 swings cannot be calculated anymore, even if the starting position is "measured to be within the size of an atom." (Percival 1993, p. 13) This property was explored by Berg (2006) and Müller (2009), who used it to generate fractal images (see figure 5.11(a)) by classifying the behavior of a Magnetic Pendulum bob above 3 magnets (Wikipedia 2007). The generation of large, screen-sized fractals from such pendulum simulations takes minutes

[23] Compare to the chaotic state of the pendulum described in section 5.6.2

to hours on current computer hardware.[24] Fortunately, avatar images are small enough to be generated in real time. This approach was also explored artistically. Kotas (2009) has created artworks since 2007 using a pendulum method. The artist explains his motivation with "Why not let gravity and motion, fluid and viscosity make the painting for me?"



(a) Magnetic Pendulum (b) Fluid Flow (c) Gravity Set

Figure 5.11: Fractals for use as player avatar image using various chaotic physical systems; generated using the *Visions of Chaos* (Softology 2010) software

Other possibilities which can be appropriated for this GPE include the simulations of diffusion-limited aggregation or chemical reactions, various fluid simulations (see figure 5.11(b)), gravity simulations (see figure 5.11(c)), lattice gas automata, and simulations of electronic circuits such as *Chua's circuit*.

Applicable GPE Principles

This GPE design lets players interactively choose fractals as avatar images. This exploratory approach constitutes an experiment (**P13**) which

[24] Berg cites 4-5 hours to generate a 1Mpixel image using his algorithm, while Müller's highly parallel GPU implementation still requires 16.5 seconds to render a 128Kpixel image.

produces observables (**P1**) displaying a high degree of symmetry and self-similarity (**P3**) while remaining visually complex (**P18**). Chaos derived from various physical systems (**P8**) exposes the player to an unstable and non-deterministic, yet physically correct representation of nature (**P7**). The creation of an aesthetically pleasing but "abstract" avatar in place of the standard human figure is a critique of traditional game design (**P25**), because it disrupts the game's hyperreality (**P10**). It may facilitate the creation of agency through the interactivity (**P21**), in particular for older players who can rationalize the abstractions. For those players, however, the GPE needs to maintain a strong connection between the graphics and the physical laws, rather than presenting "black-box" image generators without further meaning (**P20**). The technical implementation of this GPE is challenging and typically requires the use of the latest computer hardware (**P15**).

5.8.2 Fields of Charged Space

Many games, in particular older ones, use rather simple graphics, a property that establishes the traditional computer game iconography, which is often replicated in videogame art (see section 5.3). One may pose the question of whether GPEs could enhance or transform the visual aesthetics of such games. Since the iconography is based on "pixels," a GPE design to solve this task could use physical simulations that operate on spatial grids and provide aesthetic visualizations.

Laplace's Equation governs several physical problems in electrostatics, fluid dynamics or thermodynamics. In two dimensions, the equation that an electrostatic potential u must satisfy reduces to:

$$\frac{\delta^2 u}{\delta x^2} + \frac{\delta^2 u}{\delta y^2} = 0 \tag{5.8}$$

and may be solved numerically by iteratively averaging over the lattice points (*Laplacian relaxation*).[25] Pickover (1990) has suggested several ways to visualize solutions of the final potential, such as 3D terrains or contours to show the equipotential positions created by the electrostatic charge. According to Pickover, this approach creates "a reservoir from which the artists can draw," which is a clear indication of the aesthetic possibilities present in such simulations. Since GPUs can be used to implement the required 2D convolutions and operate at a very high speed (Payne et al. 2005), the simulation can now be performed directly on the pixel data inside the graphics hardware,[26] making a real-time application possible.

The proposed GPE would introduce a visualization of the electrostatic field for any game screen element as follows:

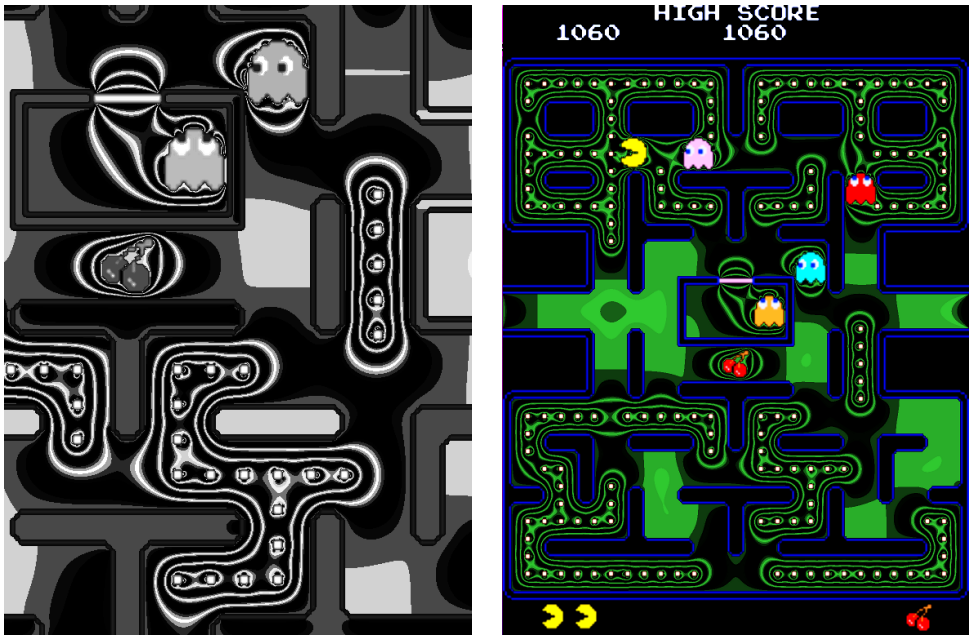
1. During the rendering pass, graphics content that is to be augmented with an electrostatic field visualization is drawn into a hidden grayscale image Q, representing a static charge distribution.
2. A *Laplacian relaxation* algorithm is applied to Q to satisfy equation 5.8. The algorithm generates a potential map U, by
   (a) binarizing Q to a map M to track at which points the potential should be held constant, and then
   (b) repeatedly averaging the values of Q or U (depending on the state of M) for all pixels by using a 4-neighborhood sum and updating U with the result.
3. Once U has converged to a stable solution, it can be used to create an overlay graphics onto the game screen. Contours may be visualized by

[25] In order to speed up the convergence of the iterative process in a *Laplacian relaxation*, computer implementations generally use a *multigrid* approach where the grid resolution increases over time.

[26] Floating-point precision for the values is generally required to achieve visually acceptable results.

applying a color map with distinct brightness-bands.

The game screen from the arcade classic *Pac-Man* (Namco/Midway, 1980) is used to illustrate the resulting aesthetics (see figure 5.12).[27]



(a) Computed Potential U (b) Final Game Screen

Figure 5.12: Electrostatic potential overlay generated using a *Laplace relaxation* applied to a screenshot from *Pac-Man*

[27] The method described in this GPE was applied to a screen capture of a typical play situation. The software to perform this calculation is included in the Proof of Practise of this dissertation.

Applicable GPE Principles

The described approach is an application of the fundamental physical laws called Maxwell's equations[28] which are generally not found in games (**P8**). The GPE can be applied to any computer game visual (**P12**), which may be aestheticized through the addition of an electrostatic field visualization generated by the application of a *Laplace relaxation* (equation 5.8) to game images (**P23**, **P26**). The real-time implementation of this GPE is only feasible on modern GPUs (**P15**). The GPE shows the intricate and dynamic nature of such fields in a very playful environment (**P14**).

5.9 Elements: Physics in Game Technology

Physics can help to improve hardware and software components that are commonly found in computer games. The corresponding GPEs add features to gaming technology that are useful regardless of game type. The GPEs could, for example, be used to enable more complex interactions with the game device or enhance gameplay in other subtle ways. This is a valid design approach, as there exist precedents such as the introduction of novel motion- and body-tracking devices like the *Wiimote*[29] (2006) or *Kinect*[30] (2010), in-game messaging software (Paul 2006), or the use of peer-to-peer systems in MMOGs (Knutsson et al. 2004).

[28]Maxwell's equations are a set of partial differential equations that form the foundation of classical electrodynamics, classical optics, and electric circuits.

[29]The *Wii Remote* is the primary controller for Nintendo's Wii console and has motion sensing capability.

[30]The *Kinect* device is an add-on game controller for Microsoft's Xbox 360 console to facilitate a natural user interface using body gestures and spoken commands.

5.9.1 Physical Entropy in Computer Games

Mechanical components of games (e.g., dice) were the first source of randomness in early scientific experiments (Galton 1890). Nowadays, computer game development uses exclusively software rather than physical systems due to the ubiquity and speed of random number generation algorithms. Digital computers are by design completely deterministic; and so to generate randomness in software, programmers implement special mathematical algorithms which produce a series of numbers that appear to be nondeterministic. These are the so-called Pseudo Random Number Generators (PRNGs). As a result, computer game design rarely makes use of physical randomness even though the games depend heavily on chance. Generally, game developers ignore the fact that randomness based on PRNGs are mere simulations themselves, and that randomness is a physical property of reality and could therefore be implemented as part of game physics. This limitation in game development can be solved through the usage of Hardware Random Number Generators (HRNGs). Since the dynamics of very small or very complex systems invariably contains some physical randomness, I suggest that games can be extended by following two GPEs which (1) provide physics-based random data to games or interactive media, and (2) extract true randomness from game-player interactions themselves. Practical implementations of HRNGs and methods for the extraction of physical entropy out of gameplay are thus described as new game physics elements.

From Chance to PRNGs

What is the role of the "element of chance" in games? While almost all modern computer games are based on strict rules (maps, game logic, linear story) they also offer interactive gameplay with unlimited possibilities. In fact, all popular genres of computer games use the element of chance as a

fundamental design choice, thereby realizing Caillois's (1962) forbidden relationship between chance and simulation (see section 4.2.3). This also matches Scheuerl's (1954) notion of *The Moment of Ambivalence* (see section 4.2.2), which states that successful game processes should be open in their result and include some unpredictability. In computer games, such ambivalence can be easily created through the introduction of random numbers into the game mechanics. Juul's (2005) analysis (see section 4.3.1) has shown that the construction of digital games is often based around Finite-State Machines (FSMs). Computer game designers make heavy use of random numbers to increase the *limited* number of states in their game's FSMs. The motivation for game design is that variation inherent in the output of PRNGs makes game simulations and behaviors of game elements appear more natural. A limited survey of source code demonstrates this ubiquitous use of PRNGs in computer games.

Ubiquity of PRNGs in Gaming

To observe the use of PRNGs in game development, I surveyed the source code of 30 open source game programs available on the Internet. A code analysis can be performed by using a text search for programming language elements such as *rand()* or *Random*. Each search result is then manually reviewed and analyzed for PRNG use. Table 5.1 summarizes the resulting statistics of PRNG use.[31] Even this limited data set clearly shows that game authors use PRNGs extensively in their game designs: the average per-game usage count is about 80. Additionally, I observed that none of the surveyed games employs non-standard[32] PRNG seeding techniques.

[31] Game sources were downloaded in July 2009. Game types: role playing game (RPG), real time strategy (RTS), first person shooter (FPS), turn based strategy (TBS).

[32] The standard PRNG seeding technique is based on the system time.

Game Name and URL	Type of Game	Platform/Language and Method Name	# of Uses
Quake2, http://www.idsoftware.com	Action/FPS	Cross/C, random()/crandom()	347
Lost Labyrinth, http://www.lostlabyrinth.com	Action/RPG	Linux/Pascal, Random()	325
Alien Arena, http://icculus.org/alienarena/rpa	Action/FPS	Linux/C, random()/crandom()	262
UFO:Alien Invasion, http://ufoai.sourceforge.net	Action/FPS	Cross/C/Lua, rand()/frand()	238
FlightGear, http://flightgear.org	Simulation	Linux/C++, rand()/sg_random()	208
Warzone 2100, http://wz2100.net	Action/RTS	Cross/C	162
Scorched3D, http://www.scorched3d.co.uk	Action/TBS	Linux+Mac/C++, rand()/random.	158
Freeciv, http://freeciv.wikia.com	Linux/C	myrand()	124
Glest, http://glest.org	Action/RTS	Linux/C++, random.	110
Freedroid RPG, http://www.freedroid.org	Action/RPG	Linux/C/Lua, MyRandom	102
Doom, http://www.idsoftware.com	Action/FPS	Cross/C, M_Random	82
Battle for Wesnoth, http://www.wesnoth.org	Action/TBS	Cross/C++, get_random/random.	67
Pysol, http://www.oberhumer.com/opensource/pysol	Puzzle	Linux/Python, .random	50
RobotRame, http://creators.xna.com	Action/TBS	XNA/C#, MathHelper.Random	46
Secret Maryo Cronicles, http://www.secretmaryo.org	Arcade/Platf.	Cross/C++, Get_Random_Float	38
Frozen Bubble, http://www.frozen-bubble.org	Arcade/2D	Linux+Mac/C++, rand()	31
Pickture, http://creators.xna.com	Puzzle	XNA/C#, RandomHelper	25
Vacuum Magic, http://apocalypse.rulez.org/vacuum	Arcade/2D	Linux/Perl, rand()	23
Super Tux Cart, http://supertuxkart.sourceforge.net	Action/Racing	Cross, rand()/RandomGenerator	22
Tennix, http://icculus.org/tennix	Action/Sport	Linux/C/Python, rand()/random.	20
RacingGame, http://creators.xna.com	Action/Race	XNA/C#, RandomHelper.	20
RolePlayingGame, http://creators.xna.com	Roleplaying	XNA/C#, Session.Random	20
VectorRumble, http://creators.xna.com	Arcade/2D	XNA/C#, random.	19
Spacewar, http://creators.xna.com	Action/Space	XNA/C#, random.	14
Primrose, http://primrose.sf.net	Puzzle	Linux/C++, randSource	10
ShipGame, http://creators.xna.com	Action/Space	XNA/C#, random.	8
Minjie, http://creators.xna.com	Boardgame	XNA/C#, random.	3
Marblets, http://creators.xna.com	Arcade	XNA/C#, random.	1
Billiards, http://www.nongnu.org/billiards	Simulation/3D	Linux/C	0
Catapult, http://creators.xna.com	Simulation/2D	XNA/C#	0

Table 5.1: PRNG usage in open source game code design (Schiffler 2010)

Randomness as Game Physics

The most important role of PRNGs is to add elements of "incomplete knowledge" or "natural behavior" to a game's FSMs. But in the physical world, one observes that automata need not have a finite number of states. For example PA use stochastic transition functions which are not deterministic (Rabin 1963, pp. 230-245) and QFA can have an "uncountable infinity of states." Furthermore, current information theory tells us that the natural world is governed by complex and unpredictable dynamic systems whose behavior is rooted in quantum mechanics. These systems cannot be accurately represented in the digital realm (Lloyd 2006). Since computer game developers have no choice but to map their designs and interactions into digital representations, they resort to simulated randomness in order to create a *natural* feel.[33] I posit that it is not difficult for games to overcome this limitation by incorporating physical properties of the environment, which are fundamentally random. Even the simplest physical systems may exhibit macroscopic randomness when their evolution over time is unstable, and external perturbations amplify exponentially (see section 5.8.1). Such systems are called *homoplectic* and many dynamical systems exhibit such behavior or can be decomposed into homoplectic components. They cause fundamentally random quantum mechanical perturbations to show up as measurable random behavior (Wolfram 1985). Based on this analysis, I argue that randomness in computer games should be treated as a form of game physics that can be based on the behavior of random homoplectic natural systems.

A game developer may question if the use of HRNGs does provide a better game experience for the player: the numerical output of a good PRNG is indistinguishable from true random sources when subjected to statistical tests such as *Ent* (Walker 2008), *Diehard* (Marsaglia 1995) or *NIST* (Na-

[33]Rogers (2001) notes, that this task is actually not without its challenges for the game developers.

tional Institute of Standards and Technology 2000). However, if one combines HRNG-use with a process that conceptually links the gameplay to the fundamental stochastic nature of our physical reality as represented by the HRNG, then play theory suggests that the experience is indeed better. As Gee's (2003) analysis (see section 4.3.3) clearly indicates, a learning context is enhanced when players have "embodied experiences that are mediated via the artificially created domains." To achieve such a linkage, the gameplay itself must be visibly used to extract randomness from the physical *player-game* system. In fact the two surveyed games without PRNG use (see last two rows of table 5.1), rely on the non-deterministic timing of player input for just that purpose.

Creating True Random Numbers

The measurement of radioactivity lends itself to the creation of a practical HRNG (Gude 1987). The radioactive decay produces measurable, independent events at random times. The generation of random bits is achieved by timing the event signals, as shown in figure 5.13 (Walker 2006). Four events are measured at a sufficient resolution (i.e., microseconds) to derive two interval durations $T1$ and $T2$ between adjacent event pairs. A single random bit is calculated using alternating comparisons $T1 < T2$ (or $T1 > T2$).[34] A uniform bit distribution is guaranteed by passing the data stream through a *von Neumann* algorithm (Davies 2000, von Neumann 1951). Multiple bits form a random number.

Various other physical entropy sources can be used to build HRNGs, such as the detection of the optical quantum effect (idQuantique 2009), measurements of thermal (Cryptography Research Inc. 1999) or atmospheric noise (Haahr 2007), and even physical processes which provide a homoplectic am-

[34]The algorithm uses alternating comparisons and discards data when $T1 == T2$ to remove systemic bias caused by the detection circuit.

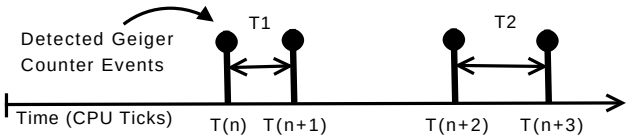


Figure 5.13: Timing sequence for random bit extraction from ionization measurements (Schiffler 2010)

plification of some unspecified random behavior, as in the lava lamp (McNichol 2003). HRNG output can be produced in the game hardware itself or retrieved from remote devices via the Internet. Web services such as *random.org*, *Hotbits*, or *playtrulyrandom.com* (see section 6.2) are available for this purpose.

Entropy of Game Processes

Even in digital computer games, randomness is inherently present due to the physical nature of the players' interactions. How could one describe a method to extract the entropy added to the game by the player? A GPE may be described as a generic procedure to generate a true random bit stream from gameplay by combining the bit extraction technique described in section 5.9.1 with a HRNG methodology based on sampling chaotic (Yalcin et al. 2004) or cyclical (Cryptography Research Inc. 2003) oscillators. If independent actions of players act as perturbance to some homoplectic state machine representing a game process, almost any computer game can be repurposed as HRNG by implementing appropriate state measurements (see figure 5.14).

- The game contains independent player-controlled processes A and B.
  - Process A generates rapidly changing state values with a sufficient resolution.
  - Process B triggers the sampling of values from process A.

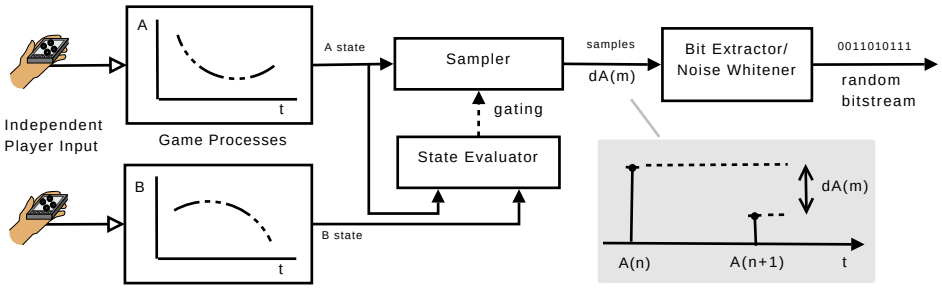


Figure 5.14: Game process entropy collector principle (Schiffler 2010)

- The usage of the sampled values is made dependent on a game-state evaluation logic, which detects concurrent player input to both processes A and B.

- Differences in the values of collected samples are used to create an unbiased random bit stream as described in section 5.9.1.

Based on the assumption that the input is truly uncorrelated, the sampler will generate a set of values that can be used to extract random bits. An algorithm that is more efficient than the simple pair-comparison described above can be used to partition the values (Peres 1992); and then one can apply an Automated Multi-Level Sub-structuring (AMLS) algorithm (Mitzenmacher n.d.) to increase the yield of random bits. This method was successfully used with radiation measurements (Crowley 2001) and is also applicable to values extracted from gameplay. As suggested earlier, the player benefits from feedback of this GPE process, for example by visualizing the gameplay-based bit generation. The generated random data could also be submitted to a Web service during game pauses, which, as Galloway has suggested (see section 4.3.4), produces brief moments of *unplay* and elevates the game to a higher form of play.

Applicable GPE Principles

The use of random numbers as a game design element is a widely used practice in computer game development. The first described GPE can be used to overcome any residual limitations of PRNGs by providing "natural" randomness (**P5**) through the usage of HRNGs. The stochastic nature of many physical processes originates in the properties of quantum mechanics, a field that thus becomes exposed to the player (**P8**). The addition of a physical HRNG to the game console (**P26**) introduces the player to concepts in modern physics (**P7**) and possibly provides an enhanced gameplay (**P10**, **P12**, **P18**). Games could also be intellectualized at a philosophical level through the exposure of the physical nature of entropy present in common game processes, as described in the second GPE of this section (**P23**). Random data extracted from gameplay may be collected and shared for use in science experiments (**P17**) through a Web service.

5.9.2 Reality Blending

Implementations of physics elements can interfere with immersion by introducing aspects of the *reality* that is outside of gameplay. Players of immersive games generally want to reach a state where the game reality dominates perception.[35] The surrounding reality is therefore seen by game developers as an obstacle which disconnects the player from the illusions they are trying to create; hence its inclusion into the game is often avoided. I posit that breaking the illusion in the game through the incorporation of reality allows the player to accept new forms of immersion, a process that improves the game experience. One possible way this could be achieved is through "reality-

[35]The corresponding state has been named Turing Event (TE) by the participants of a discussion on the game-theory website *buzzcut.com* as definition and measure for immersion.

blending" physics, e.g., the depiction of measured data or real video footage of experiments within the game. Such compositing of the fictional and the real is common in other media (e.g., many animation films mix animated characters with traditional camera footage) and popular with the audiences. For example "Reality-TV" shows like *Big Brother* (Veronica TV, 1999) and similar productions enjoy very high viewer ratings. But what type of physics can serve as the basis for a game physics element using this technique?

True Gravity

Humanity has always been interested in representations of Earth – mapping its size, shape, and composition – and the corresponding scientific field has a long history, which culminates in today's scientific discipline of geodesy, a field of physics that specializes in the measurement and representation of the Earth, including its gravitational field. The representation of gravity in games, however, has not received as much attention. Although the simulation of gravity is one of the first game physics elements,[36] and the physical constant g forms a fundamental parameter in many 2D and 3D game physics engines, its physical plausibility is reduced due to the fact that the parameter is usually set to an arbitrary value.[37] This GPE design therefore proposes to "elevate" the gravitational constant used in game simulations through physically more accurate representations that are based on geodesic models

[36]Both, the first computer game *Tennis for Two* (Brookhaven National Laboratory, 1958) and one of the first commercially successful arcade games *Space Invaders* (Taito Corp., 1978) were based on gravity simulations. See also section **??**.

[37]Most physics engines allow the game designer to precisely set the value of g, but applications developers usually chose approximate values such as 9.81, 9.8 or just $10\frac{m}{s^2}$. Also, the demos and documentation often cite incorrect units such as m/s, as in the example code of Assemblerbot (2006). Lefky & Gindin (2007) have for example shown that arbitrary values are used in the game series *Super Mario Bros.* to achieve consistent avatar motions across different consoles.

derived from measurements.[38]

No celestial object, including the Earth, is a stationary, spherical body of uniform density. Consequently the gravitational force on its surface is position-dependent. For example, one can measure $g = 9.779\ m/s^2$ in Mexico City and $g = 9.819\ m/s^2$ in Helsinki. Using an ellipsoidal reference frame, incorporating rotational forces and through many globally distributed measurements, several mathematical models have been created which describe the Earth's gravitational constant g more accurately than a single constant value. Currently in use are the *International Gravity Formula* (GRF67) and the *World Geodetic System* (WGS84).[39] These empirical formulas, such as GRF67 given in equation 5.9 (Ahern 2004), can be used to calculate the latitude-dependent[40] gravity g_ϕ.

$$g_\phi = 9.780327(1 + 0.0053024 \sin^2 \phi - 0.0000058 \sin^2 2\phi)\frac{m}{s^2} \tag{5.9}$$

Height dependent adjustments such as the Free Air Correction (FAC) or the *Bouguer correction* may also be applied to further refine gravity values obtained from these models (Fowler 2005). More recent scientific efforts include the *Gravity Recovery And Climate Experiment* (GRACE) and *Gravity Field and Steady-State Ocean Circulation Explorer* (GOCE) satellite missions, which allow the calculation of even more accurate models. Their data product is a map of the so-called *gravity anomaly* (see figure 5.15) measured in units of *mGal*.[41] It represents a correction to the theoretical gravity of

[38] Works such as "Sounds Of Gravity" by programmer Wollenweber (2007) or others explore gravity artistically as interactive audio-visual software. I believe that the inclusion of an accurate g into their simulations, would be very beneficial to the intellectual depth of these "games".

[39] The nomenclature of the models includes a date to indicate when the model was created, i.e. GRF was adopted in 1967. While WGS is dated from 1984, it was last revised in 2004 and will be valid up to about 2010 unless revised.

[40] ϕ = latitude

[41] A *gal* is a unit used in gravimetry and is defined as an acceleration of $0.01 \frac{m}{s^2}$.

an idealized and smooth Earth. Similar gravity models are also available for other celestial bodies of the solar systems such as the Moon, Mars, and Venus.

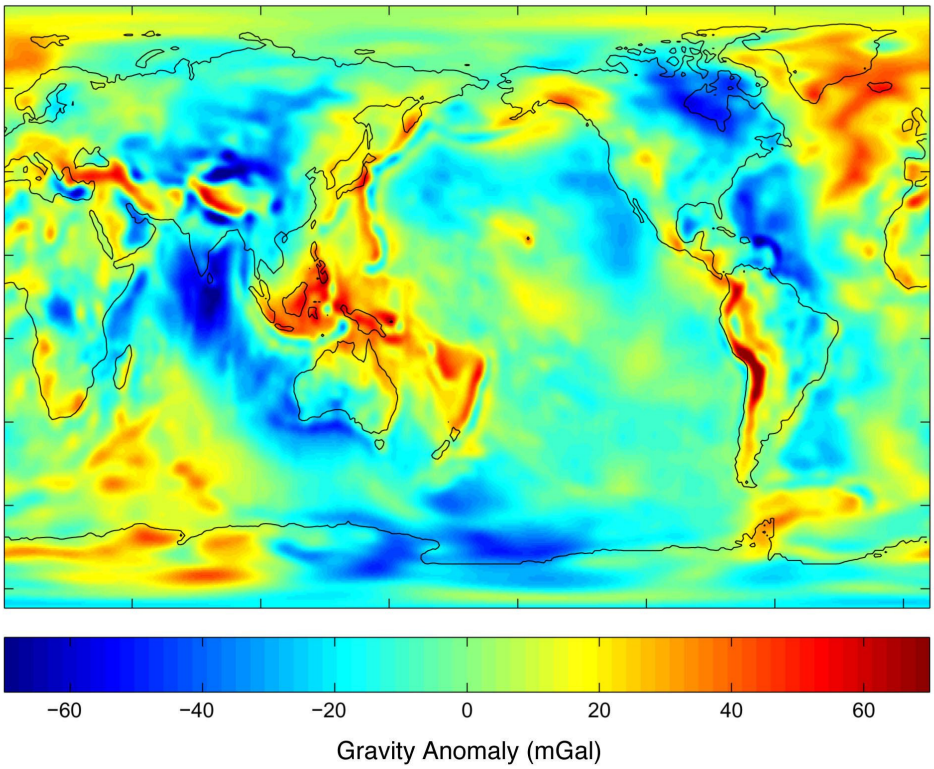


Figure 5.15: Map of the gravity anomaly as measured by the *Gravity Recovery And Climate Experiment* (GRACE) (CSR/TSGC 2004)

The proposed GPE allows the user to interactively choose a highly accurate value of g to be used in a game simulation as follows:

1. Existing empirical models of the gravitational potential for celestial bodies are integrated into the game engines using published formulae or data sets.

2. An interactive interface is designed which lets the user choose a celestial body, a gravity model, and a geographic position on the body.
3. The gravitational constant g is calculated at the chosen position and applied to the game engine's dynamics simulation.

Applicable GPE Principles

The design of this GPE blends reality into a game (**P26**) by allowing the player to explore physical datasets from geodesy (**P1**, **P8**) to set a game constant. The use of real data exposes a common simplification present in many game engines (**P2**) and forces the player to reflect on the game's hyperreality, which results from an incorrect usage of gravity in dynamics simulations (**P10**). Highly accurate numbers (**P5**) are derived from complicated mathematical models (**P23**). This fact should be exposed to the user by displaying the model's names and high-resolution gravity values, and by providing additional documentation (**P4**, **P20**). A direct connection between the science and the game can be created by downloading the latest model coefficients from the public websites of the science institutions (**P17**), a feature that is also well suited for mobile devices (**P16**). The interactive interface of this element constitutes a game-within-a-game as players can search for gravity extremes or correlate images of the planet surface with the gravity values (**P13**).

5.10 Design Framework for GPEs

A practitioner would benefit greatly from a framework that outlines how the novel game physics elements defined in sections 5.6 to 5.9 have been designed. Could one define such a methodology that links principles and designs? I believe this dissertation describes one valid approach, which treats the described principles as design guides in an otherwise free and creative game

development process, but with the goal to incorporate as many principles as possible into a new GPE in order to maximize its value across audiences. In this methodology, some principles may serve as starting points for the creation of entirely new types of game elements, while other principles are used to inform specific design choices while the game elements are constructed and their final implementation is refined. In order to provide an overview, tables 5.2 and 5.3 summarize all design principles and corresponding GPEs. The last column in the tables indicates when a particular element adheres to a principle as an *inherent quality* (**I**) of the GPE, or when the principle is merely a *design choice* (**D**) during the GPEs implementation. The summary shows that many principles can be found in both categories – either as intrinsic value or as specifically designed components of GPEs. Furthermore, some principles are particularly useful to formulate the initial design of novel GPEs, such as **P8** which calls for the usage of physics fields that have not been used in games yet. In the described GPEs, such principles have been identified as a *leading idea* (**L**) which motivated the initial core design of a particular element.

For example, the incorporation of physical entropy as a source of random numbers was the leading idea behind the GPE described in section 5.9.1 and is an application of **P5** which requires an increase in the scientific precision. Similarly, the GPE that generates choice from chaotic motion described in section 5.6.2 was motivated by **P18** as an element that introduces more ambivalence and complexity into the game using a physical system. With the initial GPE design narrowed down using one lead principle, a new element will often be automatically compatible with several other principles. For example, the experimental process a player goes through when generating an avatar from chaotic systems as described in the GPE of section 5.8.1 is inherently the application of **P13** which emphasizes the value of in-game scientific experiments. Thus, by identifying principles which are intrinsic to a GPE, one can perform a qualitative assessment of any novel game element

	Design Principle	Game Physics Element	
P1	Support the scientific method	Choice from Chaos	D
		Discovery of Cosmic Rays	D
		Avatars from Chaos	D
		True Gravity Chooser	D
P2	Indicate arcade mode	True Gravity Chooser	D
P3	Expose unity of nature	Avatars from Chaos	I
P4	Expose language of mathematics	Dilation of Time	D
		Choice from Chaos	I
		Discovery of Cosmic Rays	I
		True Gravity Chooser	D
P5	Emphasize scientific precision	Physical Random Numbers	L
		True Gravity Chooser	I
P6	Avoid fringe science	*all*	D
P7	Bridge classical/modern physics	Dilation of Time	L
		Avatars from Chaos	I
		Physical Random Numbers	I
P8	Expand physics field coverage	Dilation of Time	I
		Discovery of Cosmic Rays	I
		Avatars from Chaos	D
		Fields of Charged Space	I
		Physical Random Numbers	I
		True Gravity Chooser	I
P9	Manage fidelity of simulations	Choice from Chaos	D
P10	Mediate physical hyperreality	Discovery of Cosmic Rays	I
		Avatars from Chaos	I
		Physical Random Numbers	D
		True Gravity Chooser	I
P11	Use safe movie-physics	Dilation of Time	D
P12	Demonstrate game potential	Discovery of Cosmic Rays	L
		Fields of Charged Space	I
		Physical Random Numbers	D
P13	Support in-game experiments	Choice from Chaos	D
		Discovery of Cosmic Rays	I
		Avatars from Chaos	I
		True Gravity Chooser	I
P14	Favor education over accuracy	Dilation of Time	D
		Fields of Charged Space	I

L = Leading idea for GPE, I = Inherent Quality of GPE, D = Design Choice by GPE Implementer

Table 5.2: Summary of principles and corresponding GPEs (1 of 2)

	Design Principle	Game Physics Element	
P15	Leverage hardware capabilities	Dilation of Time	D
		Avatars from Chaos	I
		Fields of Charge Space	L
P16	Find uses for mobile devices	Discovery of Cosmic Rays	I
		True Gravity Chooser	D
P17	Support group-forming activities	Physical Random Numbers	D
		True Gravity Chooser	D
P18	Introduce ambivalence & complexity	Dilation of Time	I
		Choice from Chaos	L
		Avatars from Chaos	I
		Physical Random Numbers	D
P19	Make competitive mental challenges	Dilation of Time	I
		Discovery of Cosmic Rays	I
P20	Consider needs of adult players	Discovery of Cosmic Rays	D
		Avatars from Chaos	D
		True Gravity Chooser	D
P21	Allow non-interactive content	Discovery of Cosmic Rays	D
		Avatars from Chaos	D
P22	Allow disruption of immersion	Choice from Chaos	I
		Discovery of Cosmic Rays	D
P23	Intellectualize to abstract narratives	Dilation of Time	I
		Fields of Charged Space	I
		Physical Random Numbers	D
		True Gravity Chooser	I
P24	Enable much broader critiques	*any*	D
P25	Reduce to expose behaviors	Choice from Chaos	I
		Avatars from Chaos	L
P26	Blend reality into game	Choice from Chaos	D
		Fields of Charged Space	I
		Physical Random Numbers	I
		True Gravity Chooser	L
P27	Introduce multi-modal interactions	Discovery of Cosmic Rays	I
P28	Allow exploration of space and time	Dilation of Time	D

L = Leading idea for GPE, I = Inherent Quality of GPE, D = Design Choice by GPE Implementer

Table 5.3: Summary of principles and corresponding GPEs (2 of 2)

design. In most cases however, specific design choices need to be made by the implementers of the GPE in order to introduce additional principles. Any GPE implementation that wants to adhere to **P1**, for example, must provide measurable values in order to support the player in applying the scientific method. Likewise, any GPE that targets adult players must consider **P20** and introduce sufficient background documentation into the game to avoid being dismissed by this user group. Furthermore, the rejection of fringe science topics (**P6**) and fostering a genuine critique (**P24**) of the GPE by outsiders of gaming circles, will always be entirely dependent on the design choices made by the game developer.

Thus, the following 3 step describe a design methodology for *new game physics* elements:

1. Choose a design principle and use it as the leading idea in the design of a novel GPE.
2. Assess the GPEs applicability and value for a broad audience by matching principles found intrinsically in its design.
3. Refine and improve the GPE by applying additional principles to its design and implementation.

5.11 Chapter Conclusion

This chapter has described several new game physics elements (GPEs) in the areas of game mechanics, game story, game aesthetics and game technology, covering a wide variety of physics fields such as relativity, cosmology, electrostatics and geodesy, all of which have not been used in computer game design before. Each new GPE is related to principles for the design of game physics elements which had been formulated based on the analysis of game physics in a qualitative and quantitative way, on game theoretical approaches, and

on a review of videogame and science art. The element descriptions provide concrete implementation instructions for practitioners which are sufficiently generic to make them reusable in a spectrum of contexts, while at the same time providing a template for future game physics developments. It is my belief that the GPEs can enhance a game or interactive art installation, as outlined at the end of each GPE's description.

Some GPEs will also improve the educational value of games. Computer games and other forms of interactive environments become more empowering than traditional methods of teaching, when multiple modalities[42] are exposed to the user through them. Since several of the GPE implementations expose ways that enhance multimodal interactivity, integrating them into games would increase the games' teaching effectiveness.

The final section in the chapter proposes a GPE design framework which is based on the presented principles. The game designer would *a*) apply one principle initially to form a lead idea for a new game physics element, then *b*) use them to asses the intrinsic value of a given element design, and finally *c*) leverage them to refine the GPE's design and increase its potential. Actual implementations of some GPEs which were designed using this 3-step methodology and a critical analysis of the resulting user interactions are documented in the following chapter 6. These implementations have been realized to test selected GPEs in real game situations.

[42]Mental modalities may be comprised of visual information (images, texts, symbols, designs), sound, tactile interactions, material intelligence (empowering objects, intelligent environments) and through supporting tacit knowledge (community practice, non-verbal knowledge) (Gee 2003, pp.107-112).

Chapter 6

Prototypical Implementations

6.1 Introduction

I developed all the hardware and software products described in this chapter. While they may serve as reference implementations for some of the proposed GPEs, the primary goal was to create a research platform for field studies. The development process of the software is analyzed to discover issues that practitioners may encounter when implementing the described elements and were not anticipated during the theoretical discussion of chapter 5. The development process also illustrates what transdisciplinary work might look like, as I attempt to bridge game design with artistic and scientific approaches to physics.

I have exposed a game prototype to the three specific audiences targeted by this research: game developers, artists and scientists. A field study documented their interactions with the game and the new game physics elements using video recordings. A critical analysis and comparison of these inter-

actions is performed to identify those element designs that have the most impact on the game, to evaluate the potential of creating knowledge transfer from these elements, and to compare how the elements affect the different targeted user groups.

6.2 playtrulyrandom.com

The website `playtrulyrandom.com` (PTR) and its associated software programs implement the two game physics elements described in section 5.9.1.

6.2.1 Concept and Goals

The aim of this practical part of the dissertation was to create and operate an online service that not only provides *true* random numbers generated from HRNGs for use in games as GPE, but also collects and shares randomness originating from games. The implementation of a HRNG serves to submit random bits to the PTR service in order to fill up its repository of randomized information, also called an *entropy pool*. With the site online and the pool filled, any game would be able to introduce physical randomness by using the PTR service, thus its implementation constitutes a new game physics element. A further goal of the practical work on PTR was to include demonstrations which use this Web service to retrieve as well as to generate and submit random bits. With these demos in place, an attempt was made to collect sufficient entropy[1] from game processes, to statistically analyze and

[1]Entropy may be treated as a measure of the tendency of a process to proceed in a particular direction, for example, thermal energy that is spontaneously flowing from regions of higher temperature to regions of lower temperature. These processes reduce the state of order of the initial systems, and therefore entropy is an expression of disorder or randomness.

verify the validity of the proposed approach.

6.2.2 HRNG Implementation

The element's documentation in section 5.9.1 describes several physical processes that can be used as entropy sources. These include quantum mechanical effects at the atomic or sub-atomic level (nuclear decay, quantum optical effects), electronic thermal noise (resistors, Zener breakdown) and chaotic processes (shot noise, atmospheric radio noise, clock drift). Since one of the clearest demonstrations of random behavior in nature is the measurement of radioactivity, a practical HRNG was designed and implemented using this physical process.[2] The hardware implementation uses a device similar to the one used by the *HotBits* random number service (Walker 2006). A Geiger counter with serial port interface[3] is connected to a PC and detects decay events from the Alpha emitter of a smoke detector's ionization source. The *geigerrnd* program uses the hardware interrupt that is generated for each detection to measure the timing of these decay events with a high-resolution CPU counter. Since the physics of the nuclear decay dictates that measurements are independent from each other, the timing of the decay events can be used to extract true random bits. The software program determines time values for 4 decay events, and passes them to the bit generator algorithm described in section 5.9.1 to create one random bit. Batches of these random bits are then converted into a data stream containing corresponding "0" or "1" characters which can be submitted to the PTR Web service in regular intervals. The yield of this generator implementation depends on the detector speed and data-acquisition resolution. The HRNG for the PTR service was configured to generate about 1 bit per second to guarantee its function

[2] A radiation-based device was chosen for illustrative purposes, even though the bit yield of such a HRNG is low when compared to simple electronic devices such as the ORB (Allan 1999).

[3] RM-70, *Aware Electronics Corp.*, `http://aw-el.com`

as a high-quality source of uniformly distributed binary randomness.

6.2.3 Software Architecture

Two software components make up the PTR service and provide functionality to collect and distribute bits generated using HRNG sources:

A Website allows client-application to store and retrieve random bits in PTR's shared entropy pool. The online site exposes an endpoint API (see table 6.1) implemented in PHP: Hypertext Preprocessor (PHP) and stores data using a MySQL relational database.

A C# class provides a software interface for programmers to the PTR website and includes helper methods to facilitate random bit generation within the XNA game framework.[4]

In the current implementation, no provision is made to safeguard the random bit pool from incorrect submissions of non-random data or random data, which was generated from non-physical sources such as PRNGs. The data is also not validated in real time, but an offline analysis has been performed using statistical tools (see section 6.2.5).

6.2.4 Demonstration Game

Mlodinow (2008) posits that our brain performs notoriously poorly when reasoning over chance, random or stochastic processes. This inability affects our perception and understanding of physics, since stochastic processes are very common in nature. One can demonstrate this problem by observing

[4]XNA is a set of tools for a managed runtime environment provided by Microsoft Corporation since 2006 that facilitates computer game development.

Endpoint	Description and GET interface
index.php	Display homepage with status and image of last submission. `/index.php`
data.php	Retrieve the latest entropy pool data as raw binary blob. *source=[text]* specifies the HRNG source name. *n=[#]* specifies the number of bytes to read (max=1M). `/data.php?source=geigerrnd_ver1.0&n=32`
display.php	Generates a PNG image from entropy pool submissions. *id=[#]* specifies the pool record ID `/display.php?id=1000`
retrieve.php	Retrieve entropy pool data as string of 0/1 characters. *source=[text]* specifies the HRNG source name. *user=[text]* specifies a unique user ID (i.e., GUID). *n=[#]* specifies the number of bits to read (max=1K). `/retrieve.php?source=geigerrnd_ver1.0&user=me&n=16`
status.php	Displays the current status of PTR as webpage with image. `/status.php`
submit.php	Submit random bits to the PTR entropy pool. *source=[text]* specifies the HRNG source name. *bits=[text]* specifies the bits to submit (0/1 accepted). `/submit.php?source=test&bits=01010101`
usage.php	Track usage statistics of user by RNG mode and duration. *source=[text]* specifies the HRNG source name. *user=[text]* specifies a unique user ID (i.e., GUID). *hrngmode=[#]* indicates if HRNG was used (=1). *duration=[#]* specifies the usage duration in seconds. `/usage.php?source=MontyHallGame_v1&user=me&hrngmode=1&duration=120`

Table 6.1: Service endpoint interface of `playtrulyrandom.com` with API specifications and URL examples

people playing a class of games based on the probability puzzle called *The Monty Hall Problem*.[5] Analyzing users in the act of playing provides valuable insights for the development of game physics involving chance. For this reason – and in order to satisfy the secondary goal of this GPE, which was to use the PTR Web service to retrieve random bits – I have implemented a sample implementation of such a puzzle, called the *Monty Hall Game*. The game retrieves physical randomness from PTR and implements a version of the "Let's Make a Deal" TV show using the following four game phases:

1. The game master (computer) presents three doors and indicates that behind one of the doors is a prize.
2. The contestant (player) can pick a door; however, it is not opened yet.
3. The game master opens one of the doors from the remaining two choices. The game master selects this door so it does *not* reveal the prize.
4. The contestant may now open one of the two doors which are still closed – maybe switching from the choice made earlier – to win the prize.

When playing this game repeatedly, the player generally attempts to determine a winning strategy. The correct strategy is to *always switch* the door in step 4, however many players incorrectly assume a 50:50 chance of winning the prize irrespective of their choice of doors in this step, proving Mlodinow's point.

The game implementation requires several bits of randomness. At least 2 bits are used when choosing the placement of the prize in step 1, and sometimes an additional 1 bit of randomness is needed to simulate the game

[5] These games are named after the TV game show "Let's Make a Deal" hosted by Monty Hall. They illustrate the counter-intuitive effect of switching one's choice of doors, one of which hides a prize, if "Monty" reveals an unwanted item behind a door the player did not choose (Tierney 1991).

master's choice in step 3 for each round. The random data is retrieved from PTR when the game is connected to the Internet. The player is given a choice between true (HRNG) or simulated (PRNG) randomness as game setting and is also provided with a link to the PTR website. The wining strategy can be experimentally determined by playing the game repeatedly, since the cumulative win-loss statistics are shown on the game-over screen. While the game serves as a technical example of how to retrieve random bits from PRT, it could also be used to compare the effect of true and pseudorandom numbers on the player. However, no extensive field studies about such an effect were performed with this game.

6.2.5 Summary and Results

The PTR website was launched in 2008 and by Oct 2010, the Web service had received 384,729 submissions and had collected 49,113,970 bits in its entropy pool from the *geigerrnd* HRNG or multiplayer play of the *Pendulum Game* (see section 6.3). A detailed breakdown of the various sources of random bits is shown in table 6.2. One can clearly see that the dedicated Geiger counter device produced the bulk of the entropy data in the PTR pool.[6]

PTR	Random Bits		*ent* Statistical Tests		
Source Name	Submitted	Retrieved	Entropy	Comp.	Mean
geigerrnd_ver1.0	49,095,922	0	1.0	0%	0.4998
pendulumgame_v2	1,885	0	0.999	0%	0.4836
PendulumGame_v3	16,159	57,344			
MontyHallGame_v1	0	1,118	-	-	-

Table 6.2: Distribution and statistics of random bits submitted or retrieved at `playtrulyrandom.com`

The data submitted by the two generators can be verified using a random

[6]The values can be obtained from the database using the SQL query: `SELECT name, submitted, retrieved FROM source;`

number test program such as *ent* (Davies 2000, Walker 2008). The tests[7] against 1,000,000 bytes generated by the *geigerrnd* source and 2,235 bytes derived from both versions of the *Pendulum Game* sources show good statistical properties for entropy per bit, compressibility and arithmetic mean measures (see table 6.2). However, the gameplay-based source fails the chi-square test protocol due to a lack of data, and therefore no final assessment of this random number generation method can be made. Extensive multi-player gameplay of the *Pendulum Game* would be necessary to generate a sufficiently large entropy pool from this source to conclusively validate the proposed method.

6.3 Pendulum Game

The implementation of the *Pendulum Game* constitutes the main practical component of this research and integrates several of the proposed new game physics elements described in chapter 5 into a single game application. The element tenets of accuracy, physical rules, physical aesthetics, true randomness, reality-blending and scientific narratives are combined into a playable prototype,[8] thus creating a research platform for field studies (see section 6.4).

6.3.1 Concept and Architecture

Pendulum Game is a 2D dynamics simulation of a double regular pendulum and a double square pendulum. The goal of the game is to get the pendulum

[7] A binary file containing random bits was extracted using the *data.php* PTR endpoint (see table 6.1) and verified using the commandline: `ent /b /c file.dat`

[8] In particular, the following GPE design principles were in some form applied during the development of this game: **P1**, **P2**, **P5**, **P7**. **P8**, **P9**, **P10**, **P13**, **P18**, **P20**, **P22**, **P15**, **P23**, **P25**, **P26**, and **P27**.

to touch some "targets" at the top of the screen to collect points. A player needs to control the friction actuators in the hinges of the pendulums to inject energy into the system and make the pendulum arms swing high enough to reach these targets. A typical gameplay screen is shown in figure 6.1(a). The game features various options, including an explorative gravity environment as shown in figure 6.1(b), friction settings and a choice of random number generator type (PRNG or HRNG).

(a) Double Pendulum Screen (b) Gravity Selector Screen

Figure 6.1: Screenshots of the two primary game screens in *Pendulum Game*

The software was developed using the Microsoft XNA game development framework (Microsoft Corp., 2006) on a Windows PC. The game consists of approximately 20,000 lines of source code written in the C# language and includes extensive media content in the form of video clips, sound files, texture images, scientific data and URL databases. The operation of the game requires a high-end Windows-based computer with multi-core CPU, DirectX 9 graphics, GPU support for hardware shaders, Internet connectivity, and sound output. The game uses one or two wired *Xbox 360* game controllers; however, due to special implementation features such as Web service connectivity and real-time sound synthesis, the game cannot run on the *Xbox 360* console itself. The narrative component of the game is implemented in

conjunction with a separate application called *InfoLink Browser* (see section 6.3.5 below). The game transmits *Info Link* data over a Local Area Network (LAN) if the computer is connected to a network. The oscillatory systems together with the player interactions are used to extract entropy during gameplay in order to derive random bits that can be submitted to the PTR service (see section 6.2 above).

6.3.2 Accuracy in the Game

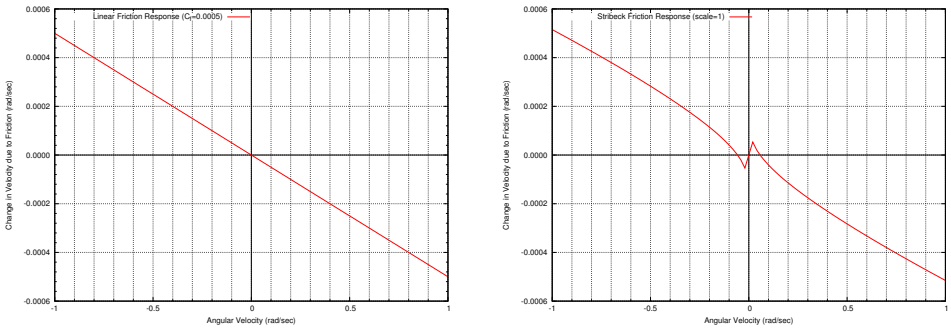
One of the goals for the game implementation was to increase the accuracy of various game physics simulations. I wanted to evaluate the impact of such a methodology on the game design process and determine if the target audiences perceive any value in such game physics. The improved accuracy was achieved by using a non-linear friction model for pendulum hinges, developing high-resolution gravity models for Earth and Mars, and simulating the effects of atmospheric density and drag on falling bodies.

Hinge Friction

Friction is the force that resists a sliding or rolling motion of one solid object over another; it is generally modeled in physics engines using a combination of static and linear dynamic friction. The static model employs a coefficient of static friction μ_{static} to determine if an object should slide, whereas the dynamic friction model uses a linear sliding friction coefficient $\mu_{sliding}$ to calculate the force counteracting the motion of the object.

A realistic pendulum model needs to take into account that friction at the hinges of the pendulum converts kinetic energy into heat, thus dampening the motion over time. Some game engines use a simplistic approach and model no hinge friction at all. For example, the swing in *Half Life 2* (Valve Inc., 2004)

is modeled in such a way (see section **??**). Most game engines, however, use the standard model which applies a counteracting torque linearly dependent on the angular velocity. This approach is advocated in most of the game physics literature, for example Eberly (2003, Sec. 3.2.7). The resulting model response is a straight line, as shown in figure 6.2(a).



(a) Standard Linear Model (b) Non-linear Stribeck Model

Figure 6.2: Angular velocity dependence of different friction models

The *Pendulum Game* extends the linear model with a more realistic, non-linear friction behavior which includes friction forces commonly used in tribology, such as Stribeck and Coulomb friction. The resulting model produces a counteracting torque with a complex non-linear behavior which is dependent on angular velocity. The *Pendulum Game* simulation simplifies a formula published by MathWorks (2010) by using only static parameters. This leads to equation 6.1.

$$\Delta\omega \propto (\omega - e^{-(\omega/0.025)^{0.3}}) + (2\omega)^{0.7}) \tag{6.1}$$

The resulting velocity-dependent friction response $\Delta\omega$ is shown in figure 6.2(b) and clearly shows a non-linear behavior at low angular velocities. As a result, the player experiences a more realistic and complex pendulum motion.

The fact that the more accurate Stribeck friction model enriches the game

is not immediately obvious, but becomes clearly apparent through a sonification of the long-term evolution of the pendulum motion. During gameplay, a state snapshot of a pendulum is used to repeatedly convert the pendulum motion into a waveform of 1-second duration, which can be played back in real time.[9] This creates a rhythmic game sound whose quality depends on the type of friction model used in the pendulum simulation. When the *Stribeck Friction* option is active, players can observe that the resulting bell-like sound is much richer as compared to the sound produced when the *Linear Friction* model is used. Even more apparent is the negative influence of the simplified *No-Friction* option on the characteristics of the synthesized audio, as it causes an annoying and unmodulated "whine" to be emitted from the speakers.

Gravity Chooser

Since the main game simulation in the *Pendulum Game* is a typical application of dynamics, it depends strongly on the gravity constant g. Rather than choosing a fixed ad-hoc value for g, the game provides the player a choice of gravitational constants for over 10 celestial bodies of the solar system. Detailed gravity models are implemented for Earth and Mars via the *Gravity Chooser* stage of the game.[10] After selecting a celestial object from the main menu, the player is provided with an interactive 3D screen (see figure 6.1(b)) that allows him or her to choose a location on the spherical surface in order to obtain a value for g from the gravity model. This game screen includes a display of the gravity value, textual information about the celestial body and gravity model used, high-quality textures of the object surface, and am-

[9] The wave data is created by running a copy of the game screen pendulum simulation over 44100 discreet time steps, sampling a state value (i.e. the deflection angle of the lower pendulum arm) in each step, and scaling this value to the correct 16bit range required for the audio playback API.

[10] For celestial bodies that have no model implementation, the same constant g_{body} is returned for any location on the surface of that body.

bient audio playback of location-specific ionospheric sounds when available (see also section 6.3.4).[11]

Gravity Models of Earth

As discussed in section 5.9.2, the physics field of Geodesy provides many models for the gravity of earth. The *Pendulum Game* implements relatively simple models such as GRF67 or WGS84 which are widely documented. In order to make use of more recent models like *GGM02* (Tapley et al. 2005), extensive research and the development of mathematical software tools was required. The International Centre for Global Earth Models (ICGEM) provides a Web interface allowing access to global gravity field models as well as theoretical tutorials. Each model is provided as a collection of coefficients for a spherical harmonics expansion of the Earth's gravitational potential W.

I contacted one of the leading physicists of the ICGEM, Franz Barthelmes, by email (pers. comm., Jan 9–27, 2009) to get assistance with the numerical methods used by the scientists. The goal was to construct a software algorithm for the game, which can calculate the gravity for any geocentric latitude ϕ and longitude λ. In the emails, Barthelmes "sketched the calculation a little" and noted that equation 6.2 needs to be solved, then a gradient of W in spherical coordinates formed. Finally, this gradient needs to be combined with the gradient of the centrifugal potential resulting from the Earth's rotation.

$$W = \frac{GM}{r}\left(\sum_{n=0}^{n_{max}}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^n \overline{P}_{nm}(\sin\phi)\left[\overline{C}_{nm}\cos m\lambda + \overline{S}_{nm}\sin m\lambda\right]\right) \quad (6.2)$$

In this equation $\overline{P}_{nm}$ are the fully normalized associated Legendre polyno-

[11] Whenever this element is used, an *Info Link* narrative event for the "gravity" topic is generated (see section 6.3.5).

mials of degree n and order m, GM is the "Earth Gravity Constant," r the Earth's radius, and $\overline{C}_{nm}$ and $\overline{S}_{nm}$ are the numerical coefficients of the model derived from measured data. Since most scientific software is made available in the computer language *Fortran*[12], the first hurdle that needed to be solved was to re-implement and validate the Legendre functions and their derivatives in the modern programming language C# used by the game. During the development, it was found that a special normalized form needed to be used to maintain numerical stability for the recursive evaluation of P_{nm}, a fact that was not apparent from the literature, such as the standard reference Hofmann-Wellenhof & Moritz (2006). Several emails were needed to obtain the commonly used value for the angular velocity of the Earth.[13] When the values generated by the final algorithm did not match those calculated by ICGEM, Barthelmes explained at length that the models include "unstable coefficients" and provided this comment on how to resolve the problem:

> To cut a long story short ☺: I would take the coefficients of the model `ggm03s` up to $l = 120$ **only**. (pers. comm.)

In summary, the implementation of a modern gravity model as a game physics element has involved interactions with scientists and the use of scientific literature. The issues encountered highlight the difficulties a game developer is likely to face. Scientific data, software and background information is often not easily usable since it requires much domain-specific knowledge, secondary data sources and many mathematical tools, which are often not available to a game developer. The final implementation of the Earth's gravity model in the *Pendulum Game*'s gravity chooser uses a grid-interpolation approach and data pre-calculated using the ICGEM Web service, rather than

[12] *Fortran* is a general-purpose, procedural programming language suited for numeric computations and was originally developed by IBM in the 1950s for scientific and engineering applications.

[13] Geodesy uses $\omega = 7.292115 \cdot 10^{-5} \frac{1}{s}$ from WGS84, which is not exactly $2\pi/(24*60*60)$.

a direct calculation of g from the model coefficients outlined above, due to the unstable nature of the C# algorithm.

Normal Gravity on Mars

A formula for the latitude-dependent gravity model of Mars is not readily available in the literature; therefore the game design process required the derivation of a model equation. Using advice and references provided by physicist Alex Konopliv of JPL (pers. comm., Oct 11–15, 2009), who is an expert on Mars gravity, an accurate model could be derived. The latitude-dependent normal gravity $g(\phi)$ for an elliptical body with flattening f, semi-major axis r and rotation rate ω can be expressed in terms of the equatorial gravity g_0 by the following linear approximation provided by Hofmann-Wellenhof & Moritz (2006, pp. 77–81):

$$g(\phi) = g_0(1 + f^* \sin^2(\phi) - \frac{1}{4} f_4 \sin^2(2\phi)) \tag{6.3}$$

where

$$f^* = f_2 + f_4 \tag{6.4}$$

$$f_2 = -f + \frac{5}{2}m + \frac{1}{2}f^2 - \frac{26}{7}fm + \frac{15}{4}m^2 \tag{6.5}$$

$$f_4 = -\frac{1}{2}f^2 + \frac{5}{2}fm \tag{6.6}$$

$$m = \frac{\omega^2 r}{g_0} \quad and \quad g_0 = \frac{GM}{r^2} \tag{6.7}$$

Inserting the currently available measurements for Mars[14] into the above equations, I have simplified the formula to equation 6.8. The resulting normal

[14] $GM = 42828.35796\ \frac{km^3}{s^2}$, $f = 0.005079304192$, $r = 3397.0\ km$, and $\omega = 7.088218081 \cdot 10^{-5}\frac{rad}{s}$ (Huber & Beebe 2009)

Latitude	Gravity (m/s^2)
0°	3.7114219
10°	3.7121409
20°	3.7142127
30°	3.7173919
40°	3.7212998
50°	3.7254685
60°	3.7293950
70°	3.7326026
80°	3.7346995
90°	3.7354283

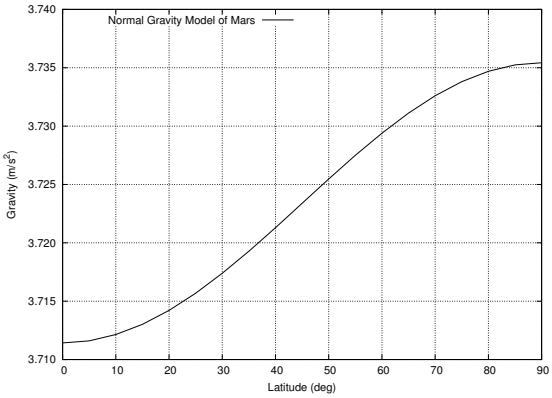


Figure 6.3: Latitude-dependent normal gravity model of Mars

Mars gravity estimation exhibits latitude dependence as shown in figure 6.3.

$$g(\phi) = 3.7114219 + 0.02400635 \sin^2(\phi) - 4.2212837 \cdot 10^{-5} \sin^2(2\phi) \ \frac{m}{s^2} \quad (6.8)$$

Formula 6.8 is used as default choice for the gravity model of Mars in the *Pendulum Game*'s options. The fact that this model is only dependent on ϕ and thus is less sophisticated than the Earth's model, which depends on ϕ **and** λ, can be experimentally explored by the player in the *Gravity Chooser*.

Atmospheres

Most game dynamics simulations – apart from flight-simulators, driving games, and cannon games – tend to neglect or simplify atmospheric effects such as drag, air density or turbulence on objects. The only *other* use of physics-based atmospheric effects in commercial games are particle-simulations of fog and smoke which are common aesthetic components used to provide "eye candy" to the game without affecting gameplay in any significant way. One

of the reasons for this game design limitation is the difficulty to evaluate drag coefficients for arbitrary objects. It is a calculation that is very difficult to implement. In addition, it seems nearly impossible to obtain software that *can* perform this calculation, probably due to its military application. The *Pendulum Game* uses a simulated atmosphere to accurately account for the effect of drag on moving objects.

The drag simulation in the *Pendulum Game* relies on the fact that game objects use simple shapes and their movements are constrained to 2D space. In this simplified case, the drag force F_d which an object of cross-sectional area A experiences when moving through a gas or fluid of density ρ at relatively large velocity v, can be estimated using the *drag equation* 6.9. F_d acts in a direction opposite to the incoming flow velocity. The *drag coefficient* C_d, a dimensionless parameter, is taken from a table containing empirically determined values for many simple geometric shapes (Clancy 1975).

$$F_d = 0.5\rho v^2 C_d A \tag{6.9}$$

In order to incorporate this drag effect into the *Pendulum Game*, nominal atmospheric densities for all celestial bodies are made available to the game simulation. For example the atmosphere of Venus has a density $\rho_{venus} = 67kg/m^3$, which is about 6.5% that of liquid water on Earth, and produces a considerable drag effect. Since the target objects in the game are spheres, a constant drag coefficient for a circular shape of $C_d^{sphere} = 0.47$ can be used. This additional sophistication in the dynamics simulation causes falling objects to accelerate smoothly until they reach a constant terminal velocity. This sets up an in-game experiment, where the player can experience a dependence of the terminal velocity on weight and atmospheric density, as

determined by the material of the spheres[15] and the celestial body, respectively. The simulation based on equation 6.9 still represents a highly simplified approximation of physical reality, since it does not take into account the effects of a buoyancy force, any speed dependence of C_d (Reynolds number dependence), or the linear Stokes' drag at slow speeds. The effect of the atmosphere on the motion of the pendulum bobs – a potentially subtle but important effect – was not considered in the game either. A derivation of modified equations of motion for the pendulums that include atmospheric drag is beyond my expertise, and no such equations have been published in the literature.

6.3.3 Physical Rules

As the name of the game indicates, a physical simulation of a pendulum is the main game element in the *Pendulum Game*. A double pendulum system was chosen because it provides aesthetically rich motion dynamics, serves as an educational example of chaos in physics and can be used to provide rapidly changing oscillatory values for the game-process-based HRNG implementation. An additional physical rule was employed to create a novel and easy-to-understand interaction method for the user. This method uses a rotational-friction drive simulation, which interacts with the pendulum.

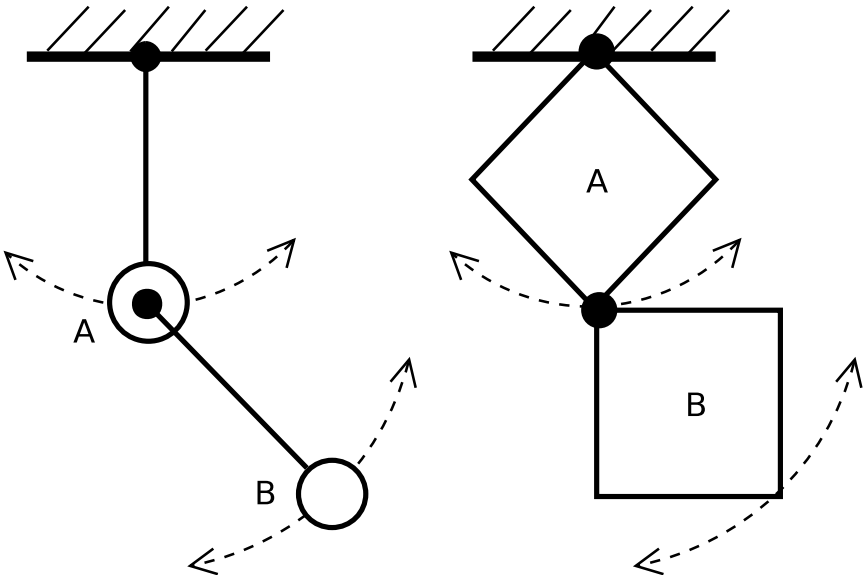
Double Pendulum

A double pendulum is a simple dynamical system where one pendulum is attached to the end of another pendulum. Such systems exhibit chaotic behavior at certain energies.[16] The dynamics implementation of the *Pendulum*

[15] The game uses representations of gold, silver and copper spheres. Their mass number is calculated accurately from the density and size of the spheres.

[16] The total energy of the pendulum is the sum of the kinetic and potential energy of all of its components.

Game simulates two different types of pendulum systems. One system is a *Double Regular Pendulum*, where two components, A and B, comprised of a bob attached to a rigid limb of negligible weight, are connected and suspended via hinges in the limbs (see figure 6.4(a)). The other system is a *Double Square Pendulum*, where two square masses, A and B, of equal size and negligible thickness, are connected and suspended via hinges placed in the corners of the squares (see figure 6.4(b)).



(a) Regular Double Pendulum (b) Square Double Pendulum

Figure 6.4: 2D composite pendulum systems with two elements A and B which can rotate around hinges (•)

If these systems are idealized by neglecting the dimension and mass of the hinges as well as the mass of the connecting rods, the equations of motion can be easily derived (Neumann 2004). Weisstein (2007), for example, has published a model for the angular acceleration $\dot{\omega}$ of a double regular pendulum as equations 6.10 and 6.11. Subscripts 1 and 2 refer to the top and bottom component, respectively; ω denotes the angular speed of rotation of angle θ, Δ the difference $\theta_1 - \theta_2$, m is the mass of a bob, l the limb length

and g the common gravitational acceleration of the environment. Equivalent equations for the square double pendulum are documented in much the same way by Wheatland (2007) and Rafat et al. (2009).

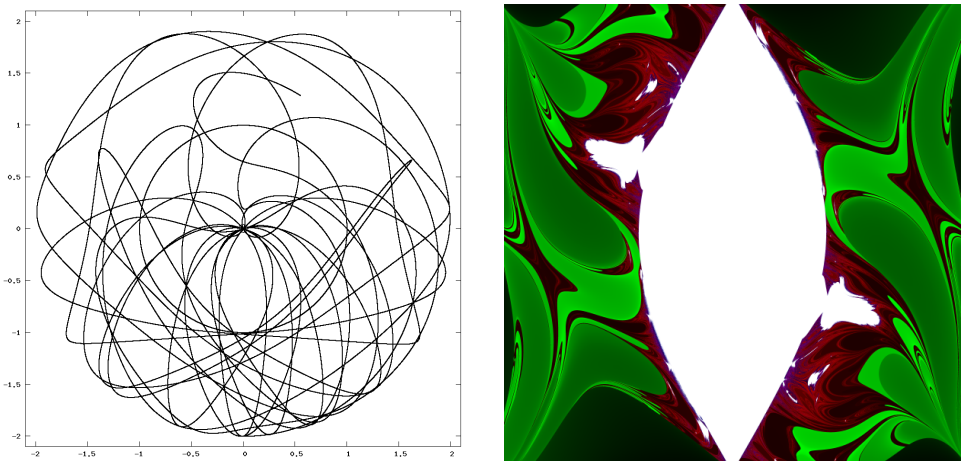
$$\dot{\omega_1} = \frac{-g(2m_1 + m_2)\sin\theta_1 - m_2 g \sin(\Delta - \theta_2) - 2\sin\Delta m_2(\omega_2^2 l_2 + \omega_1^2 l_1 \cos\Delta)}{l_1(2m_1 + m_2 - m_2\cos(2\Delta))} \tag{6.10}$$

$$\dot{\omega_2} = \frac{2\sin\Delta(\omega_1^2 l_1(m_1 + m_2) + g(m_1 + m_2)\cos\theta_1 + \omega_2^2 l_2 m_2 \cos\Delta)}{l_2(2m_1 + m_2 - m_2\cos(2\Delta))} \tag{6.11}$$

Iterative methods for the approximation of solutions to ordinary differential equations can be used to determine the dynamic evolution of the pendulum system over time. The 2D simulation algorithm in the *Pendulum Game* uses the Nyström modification of a fourth-order Runge-Kutta method (Dormand & Prince 1987) to generate an accurate approximation for the above set of differential equations for discrete time steps. The resulting pendulum motion is calculated in real time during the game loop and produces a complex trajectory (see figure 6.5(a)).[17] The system exhibits deterministic chaos, as illustrated by the fractal shown in figure 6.5(b).[18]

[17]The motion creates a challenge for the player. Whenever the element is shown, an *Info Link* narrative event for the "pendulum" topic is generated (see section 6.3.5).

[18]Each pixel in the fractal image is colored according to the time it takes for either bob of the unit double pendulum to flip over. The pixel position corresponds to the initial deflection angle of either limb over the range $[-\pi, \pi]$ (Heyl 2006).



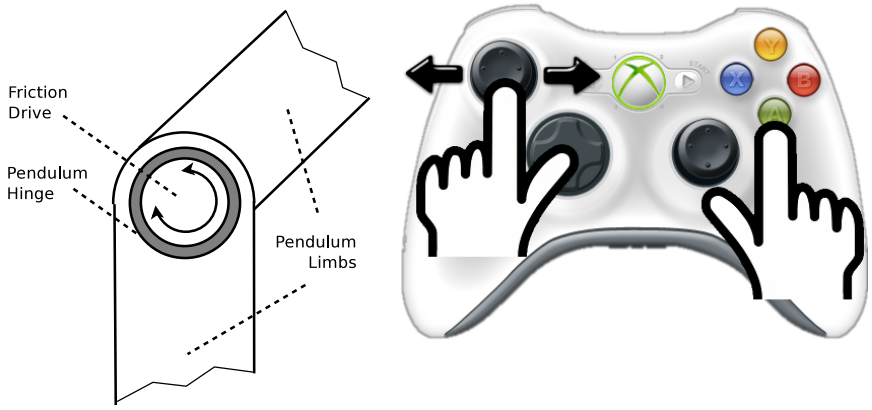
(a) Bob Trajectories (b) Flipping Behavior

Figure 6.5: Chaotic dynamics of the unit double pendulum as visualized by a path (left) or a fractal (right)

Friction Drive

The *Pendulum Game* implements a hypocycloidal friction drive simulation, which allows the user to interact with the pendulum. In this simulation, the player controls the speed of an actuator ("drive") placed inside the hinges of the pendulum (see figure 6.6(a). The model assumes that the rotation occurs inside a plain bearing using hydrostatic lubrication, so that the frictional coupling between the drive and the hinge can be modeled using a simple linear relationship (Beardmore 2009). Due to the friction present in the bearing, the player can displace either pendulum limb in the direction of the drive's rotation and thereby accelerate the pendulum and inject energy into the system, or slow the pendulum and remove energy from the system. During gameplay, the player uses the *Xbox 360* controller's analog stick shift to determine the speed of the simulated drive and the A (green) & B (red) buttons to selectively choose either the top or bottom hinge (see figure 6.6(b).

Not considered in this model is the physical construction of such a drive (energy source, weight), additional dynamic effects (inertia, collisions) or other mechanisms of energy loss.[19].



(a) Friction Drive (b) *Xbox 360* Controller

Figure 6.6: Friction drive simulation (left) connected to a game controller (right) as user interface

6.3.4 Game Technology

The *Pendulum Game* implements several GPEs with a game technology focus as discussed in section 5.9.

Randomness

The game is both a consumer and producer of random numbers and communicates with the *playtrulyrandom.com* (PTR) Web service described in

[19] According to Peters (2001) for example, many oscillator models do no consider energy loss *within* their structural members.

section 6.2. Using an Internet connection, random bits are retrieved from the Web service and used to randomize the material of the targets ("balls") in the game, to select a random pendulum video for the game-over screen, and to pick one of the many URLs from the database when requested by the *Info Link* component of the game. The player can also choose to use a simulated source of randomness instead of the PTR service.[20]

The pendulum system is used as a HRNG through the entropy collection method of section 5.9.1. A pendulum that exhibits chaotic motion provides a perfect oscillatory input to the described algorithm. The energy of the pendulum together with a tracking of user activity is used to gate the sampling of numeric values. Entropy is thereby extracted from two-player gameplay and collected by the PTR Web service. As visual feedback for the player, the collected entropy bits are displayed on the game screen in real time and a summary stating the counts of consumed vs. produced random bits is shown on the game-over screen.

Reality Blending

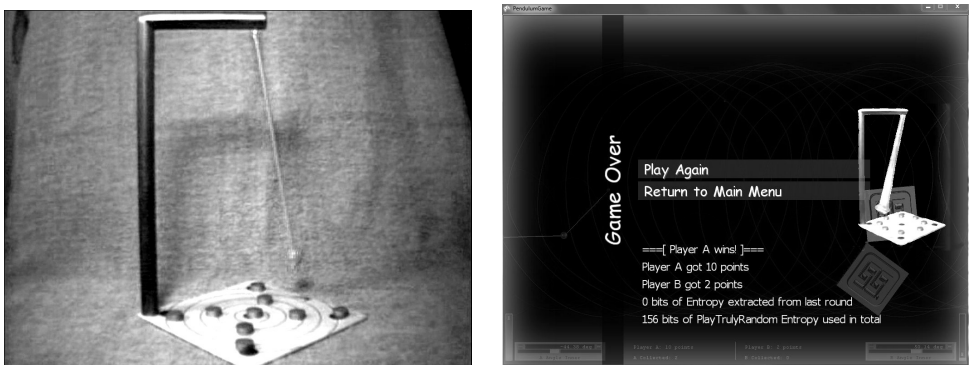
The element of "reality blending" is incorporated into the *Pendulum Game* in several ways. The video footage of a magnetic pendulum is integrated using a Chroma key effect. The planetary surfaces that are displayed during the gravity selection stage are represented using high-quality planetary texture maps derived from actual research imagery. Furthermore, the game uses a different texture of the Earth for every month of the year.[21] An overlay of sounds from audible ionospheric measurements was applied to the gravity selection for several celestial bodies including Sun, Earth and Jupiter.

[20] Whenever the element is used, an *Info Link* narrative event for the "randomness" topic is generated (see section 6.3.5).

[21] The choice of textures is synchronized with the actual time of the PC.

Pendulum Video

This "reality-blending" element was added by mixing video footage of the *R.O.M.P.* magnetic pendulum toy (HogWildToys 2001) into several game screens. Various clips of the magnetic pendulum toy were first recorded using a standard digital camera and then converted into a video format that is supported by the XNA framework. The pendulum footage was taken in front of a uniformly colored background (see figure 6.7(a)), in order to be able to use Chroma key compositing of the video in any game screen. The game implements a GPU-based Chroma key effect using a High-Level Shader Language (HLSL) function (see Appendix H for source code). This shader effect can be used to apply a Chroma key in real time to a video stream.[22] In the actual implementation, the pendulum footage was blended into the *Game Over* screen (see figure 6.7(b)).



(a) R.O.M.P Video Footage (b) *Game Over* Screen

Figure 6.7: GPU-based Chroma key effect to blend actual pendulum video (left) into a game screen (right)

[22]The shader implementation calculates the pixel transparency as a step transition at the threshold value of the difference between the pixel color and a reference color.

Ionospheric Sounds

Celestial bodies are often surrounded by ionized gas called an *ionosphere*. The ionized gas of ionospheres contains pressure waves whose acoustic spectra can be measured and transposed into the audible frequency range.[23] Another way in which ionospheres can "produce" sound is by excitation, such as from lightning or the influx of high-energy electrons into the magnetosphere. These processes create Very Low Frequency (VLF) electromagnetic waves in the plasma, which can be converted to audible sound using a suitable receiver. The more structured sounds produced in this way, called "Sferics," "Tweeks," "Whistlers," and "Chorus," are layered on top of a more constant background noise called "Hiss" which is generated by the auroral zones of the ionosphere (McGreevy 2007). For example, audio clips for the planet Saturn were obtained from the NASA website and are based on signals received by a plasma wave science instrument on the Cassini spacecraft measuring the radio waves emitted by Saturn's lightning storms (NASA 2009).

Using these audio files, the *Gravity Chooser* element is augmented with a sound overlay of ionospheric sounds.[24] Each audio track is specific to the celestial body that is being shown. The inclusion of a sonification provides a multi-modal representation of the planet based on actual measurements, and the game design thereby "blends" physical reality into the interactive experience.

[23] See for example the methods used in the art installation *"sonification"* created by Bodle & Erickson (2005).

[24] Credits for the audio files belong to the following sources: *r a d i o q u a l i a*, New Zealand; *Windward Community College Radio Observatory* (WCCRO), Hawaii, USA; *NASA's Radio Jove network*, USA; *Ventspils International Radio Astronomy Centre* (VIRAC), Latvia; *RIXC*, Latvia; *University of Iowa's Plasma Wave Group*, USA; *Jodrell Bank's Pulsar Group*, UK

6.3.5 Scientific Narratives

Due to the fact that the *Pendulum Game* uses "action-style" gameplay in the gravity chooser and pendulum controls, it is difficult to integrate a traditional story-based narrative into the game. Media research has recognized, however, that digital narratives in games are no longer necessarily linear but rather form an integral aspect of the gameplay's "performance" (Smith & Curtin 1998). This mirrors a process that is common in physics research, where a new argument or theory is constructed "non-linearly" by continuously collating information from various sources. The game conceptually provides such an approach to narration through the *Info Link* component.

Info Link

The implementation of the narrative element named *Info Link* consists of a software component that generates contextual (topical) broadcasts of narrative fragments triggered by game events. These fragments are sent over the network and received by a "browser" application (see figure 6.9), which can be used by the player or bystanders to construct and navigate the narrative during gameplay. The *narrative producer* consists of an Extensible Markup Language (XML)-based database containing links on game-specific topics. An individual link is selected randomly within the topical context provided by the game event (i.e., when a gravity value is chosen by the player, an event with the context "gravity" is created) and a data packet is sent over the network using User Datagram Protocol (UDP)-multicasting (see figure 6.8). This design simulates a physical system emitting information quanta, and it allows any device connected with the network to become a probe, thus simulating an experiment. With this technique, any *narrative consumer* with a corresponding UDP receiver may read the links off the network and display the narrative information contained within. A user may not even see the ac-

tual gameplay, but can still participate in the game through the presented narration.

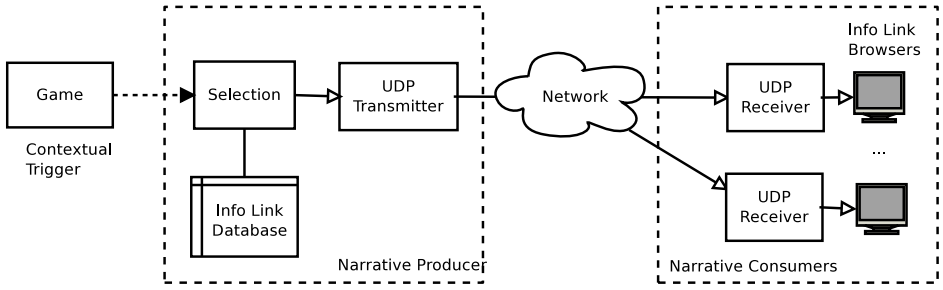
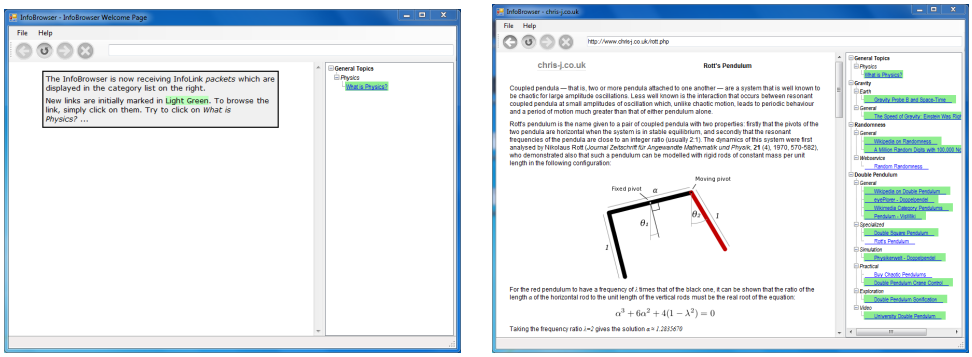


Figure 6.8: Block-diagram of the *Info Link* system for contextual "broadcasts" of narrative fragments

During the field studies of the *Pendulum Game* (see section 6.4), a separate application called *InfoLink Browser* (see figure 6.9(a)) is run on a second computer. It is connected to a LAN and configured to collect all narrative broadcasts generated by the *Info Link* system during gameplay. I populated a database in *Pendulum Game* with an extensive link collection about the topics of gravity, randomness and double pendulum systems, thus providing game-relevant physics content.[25] Each of the data packets contains a URL of a website, a title and a two-level categorization, which is similar to the way scientific articles are referenced. The categories can be used by the browser to aid the user in navigating the received content. The latest links that have been received are color-highlighted in the browser application. All links may be saved to provide a record of the gameplay. However, the main purpose of the links is to enable the user to create a narrative by clicking on the links to view the content they point to (see figure 6.9(b)). The reader thus creates a link "trail" (the narrative) and *may* contribute to the gameplay by instructing the game player. In summary, the combination of game-driven topic generation, content organization and information browsing creates a

[25]The included links were found through manual web searches and selected based on topical accuracy, relevance, quality of content and other attributes deemed valuable for the player.

game narrative based on physics content. The *Info Link* system constitutes a kind of "physics experiment" in which the player "probes" the domain-specific scientific data emitted from the game during the play.



(a) Start Screen (b) Browsing Links

Figure 6.9: *Info Link* browser as interface to a *physics* narrative

Science-Oriented Designs

The game is designed to resemble an experimental setup and thus creates a scientific semiotic domain. Physics-based content which is used or displayed in the game has a corresponding source reference (author name or URL to website) to give the user the possibility to follow up with further reading or to validate the information. Data values are always shown with their respective physical units, and the source code documentation references units when applicable. The pendulum trajectory is visualized using "chart plotter"-style graphics to mirror an aesthetic found in the instrumentation of physics experiments. The user is also provided with the ability to interactively choose which variable of the simulation is being displayed during gameplay (e.g., angle or speed). This feature, together with the possibility to log simulation data into a file for later analysis, is a prerequisite for educational uses of the game.

6.3.6 Summary and Results

The *Pendulum Game* incorporates many of the proposed "new game physics elements" into a playable game and thereby creates a research platform for field studies (see section 6.4). The Windows-based game executable is available for download to the public[26] and can be used for future research or to get additional user feedback about the implemented GPEs. Since the game is delivered as open source software, individual elements or the entire game can be reused, modified, extended or used in "mashups" by other game designers, scientists and artists. The entropy that was generated during gameplay and collected by the *playtrulyrandom.com* Web service (see section 6.2.5) may be shared for other uses, including scientific ones.

6.4 Field Study

As part of this dissertation, a field study was conducted, which allowed different focus groups to play the *Pendulum Game* application, while the interactions were video-recorded. This section summarizes this study and then draws relevant conclusions from the analysis of the available video documentation.

6.4.1 Focus Groups and Physical Setup

The primary consideration in selecting members of the focus groups was their membership in one of the three communities potentially involved in new game physics design: artists, game developers, and scientists. Further factors such as age and gender, while potentially relevant, were not considered in this field study, because the intent was to trigger interactions with the new

[26] See `http://www.ferzkopp.net/PhD`

game physics elements, and to compare the behaviors of the different target groups. Several *artists* were shown the game and asked to provide feedback. This group was chosen since artists tend to create gaming interactions or investigate scientific topics in novel ways and with different goals than either game developers (commercial games) or scientists (serious games), as outlined in section 5.3 and 5.4. The resulting artists group consisted of 14 people from the Z-Node PhD program. In addition, several children[27] were also part of this group. Several *game developers* were asked to participate in the field study, since they produce most of the games in use today and define the status quo of game physics. The 7 resulting candidates were all members of an informal local group of professionals who gather at a monthly "meetup" event to discuss game development. These candidates played the game at one of the events. A group of *scientists*, 6 physicists, was also invited to play the game. This group was chosen since physicists are the originators of many of the theories that form the basis for several of the proposed GPEs. They may also be beneficiaries in a successful application of new game physics for teaching purposes. The game was demonstrated during a seminar class held at the University of Washington (UW) Chemical Engineering department.

The goal of each study was to engage members of the test group to play the *Pendulum Game*, to observe their behavior and to collect feedback. The game author launched each meeting by presenting the game and remained present to provide user assistance during gameplay. Two different physical setups were deployed. **Setup 1** was used with the group of artists and consisted of a game PC, a large projection[28], a professional sound system, two *Xbox 360* controllers and a second PC connected via a LAN running the *InfoLink Browser* application. **Setup 2** was used with the group of game developers as well as the scientists and consisted of a game laptop with built-in speakers,

[27] The children were family members of the artists and between 6 and 12 years of age.
[28] Using a professional-grade Digital Light Processing (DLP) projector.

a medium-sized projection,[29] and two *Xbox 360* controllers. This setup did not have an Internet connection or a second browser screen. All interactions were recorded using a digital camera and later post-analyzed and assembled into a video documentation (available on the enclosed DVD).

6.4.2 Summary of Video Documentation

Although the obtained video material was limited in scope (about one hour of footage for each group) and quality (some audio and lighting issues were present) it was sufficient to document the field study of this dissertation. The final DVD contains about $1/6^{\text{th}}$ of the total source material in selected video segments.[30] These segments show all stages of the gameplay within the *Pendulum Game*, demonstrate standard gameplay situations, document the questions that were asked about the game, and show other interactions which are directly connected to the game, game physics or a particular play situation.

The following tables provide an index to the documentation, which is split into four parts. Part 1 (see table 6.3) demonstrates and explains the *Pendulum Game* in detail as narration. Parts 2 to 4 (see tables 6.4, 6.5 and 6.6) summarize the field studies with artists, game developers and scientists respectively.

6.4.3 Observations and Results

The analysis of the video documentation of the field study provides a range of results relevant to this research. The *Pendulum Game* created interest in

[29] Using a consumer-grade Liquid Crystal Display (LCD) projector.

[30] Source material which had to be removed from this summary had either a low video quality (i.e. too dark), contained material already included in other parts of the documentation, had unusable audio or did not provide any new game relevant user interactions.

Time	Description
0:36	Introduction to game and *Main Menu* screen
1:19	*Help* screen and explanation of game controls
1:40	*Game Information* screen and gameplay summary
2:21	*Pendulum Video* menu option
3:00	Playing the game with *Start Game* selection
3:10	Explanation of game option *Celestial Object*
3:38	Explanation of game option *Gravity Model*
4:09	Explanation of game option *Friction Model*
4:30	Explanation of game option *Entropy Source*
4:57	Gravity selection with *Choose Gravity* selection
5:12	Demonstration of the *Gravity Chooser* screen
6:29	Overview of the *Game Screen*
7:01	Explanation of the goal of the game
8:04	Discussion about the pendulum animation
8:49	Completing the game and the *Game Over* screen
9:26	Details on using the Xbox controllers
9:48	Details on specific pendulum motion patterns
10:06	Details on the actions a players can take
10:27	Details on the friction actuators
10:44	Discussion of game strategies
12:02	Introduction to the *Info Browser* concept
12:47	The *Info Browser* application screen
13:13	The *Info Browser* player experience

Table 6.3: Index to video documentation of *Pendulum Game*

all three groups to play with the simulation. The interface was easy to use for all players and required minimal instructions, despite the fact that most members of the focus groups had never handled a game controller before. The gameplay seemed engaging to most users, as demonstrated by the extended time many participants spent with the game. Several users played for up to 30 minutes continuously and some requested a copy of the software for their home consoles or computers.

Players recruited from the artists group as well as children showed a much greater openness to explore the game, for example by spending much more

Time	Description
17:00	Start of documentation on artists
18:12	Author provides info about documentation slides
18:22	Author provides info about the gameplay
19:14	Author provides info about the gravity selector
20:00	Open play situation
21:35	Two-player gameplay situation
23:45	AQ1: Question about gravity number
24:15	AQ2: Question about "ringer"
24:34	AQ3: Question about "light planet"?
24:58	GP1: Situation with circular motion on moon
25:25	GP2: Situation with pendulum in chaotic motion
26:12	GP3: Situation with player body motion

Table 6.4: Index to video documentation of artists group

Time	Description
26:45	Start of documentation on game developers
27:08	GP4: Situation giving controller explanations
27:55	GP5: Discussion on color 3D effect
28:35	GP6: Discussion on overcoming chaotic motion
29:05	GP7: Comments on line graphics
29:45	GP8: Situation with player body motion
30:10	GP9: Situation playing on sun, with noise
31:03	DQ1: Question on entropy markers
31:30	DQ2: Question about gravity on sun
31:55	DQ3: Question about cosmic noises
32:25	DQ4: Question about performance issues
33:00	Suggestions for game improvements
34:02	Positive feedback
35:10	Negative feedback
36:10	General feedback

Table 6.5: Index to video documentation of game developer group

time in the *Gravity Selector* screen. One could also observe that players from the artists and scientists groups both felt compelled to introduce "body motion" during gameplay, a behavior which was not observed with game developers. The reason for these differences is likely the "task oriented"

Time	Description
37:52	Start of documentation on scientists
38:15	GP10: Situation explaining friction as "brake"
38:55	GP11: Situation comparing motion to gymnast
40:28	GP12: Situation with "good" motion and cheering
41:14	SR1: Researcher mimicking, analyzing, and suggesting
42:02	SR2: Researcher discussion rotation on moon
42:35	SR3: Reflections on entropy and coupled processes
43:45	SQ1: Question on relation of motion and friction
44:25	SQ2: Question about Stribeck parameters
45:06	SQ3: Question on location of mass and Centroid?
45:54	SS1: Suggestion to teach and give more info
46:38	SS2: Suggestion to use Maxwell springs or electric circuits

Table 6.6: Index to video documentation of scientists group

approach the scientists took in trying to understand the game and manage the abstract interactions. For example, scientist players clearly attempted to deconstruct the motions of the pendulum to aid in play (e.g., see SR1). Similarly, game developers appeared primarily focused on winning the game and treated the gameplay as a competitive situation. Accordingly, this group showed little motivation for experimentation with the game physics elements. In contrast, the artists group felt much more compelled to explore the game's interactive potential and experience the "texture" and aesthetic content it provides. Artists showed significant interest in the visual components of the game. This interest was also shared by game developers, but with a different focus. Developers provided comments on technical aspects of the visual design and provided direct modification ideas. All groups shared the same visual association with the regular double pendulum, which was seen as a representation of a "training gymnast."

Regarding feedback about the game and gameplay, both game developers and scientists immediately suggested changes to the game, providing ideas on game design improvements or additional physics simulations respectively. In

contrast, no such comments were received from the artists. This indicates a significant difference in how the groups approach their criticism, with artists being more reserved and cautious to request modifications to the "work." It may also suggest a different level of comfort and knowledge about the medium of "games" or the topic of "physics" by the artists as compared to the other two groups. Some of the proposed changes to "improve the game" by game developers, such as imposing time limits or adding computer-controlled "agents" to the gameplay, would destroy the experimental situation that the game offers and therefore diminish the game physics elements. Accordingly, these changes would have made the game less valuable for the scientific community as an educational tool, in particular since several of the players in the scientists group performed consciously scientific experiments within the game (i.e., let the pendulum swing freely to understand the physical laws controlling it). In contrast, neither artists nor game developers performed in-game experimentation at this level. Consequently, I conclude that the design of the game did provide some gameplay components that catered to physicists and were valued by the science group.

Members of all three focus groups had some questions about the game. The artists and game developers requested basic science background information (e.g., what does a gravity of "7" mean), whereas the scientists requested advanced scientific details (e.g., questions about the parameters for the Stribeck curve used by the friction coupling). This is an expected difference, as the scientists were either familiar with the physics involved or did not want to ask basic questions in front of their peers. Game developers often requested information about game-related technical details (e.g., the nature of entropy markers on the screen) including very specific ones about solutions to software-performance problems.

Game developers appeared to connect very well with the game physics theme of the game, but were the only group to criticize the game itself as

"boring" or in need of more conventional gameplay elements. Consequently the suggestions provided by the game developers focused on technological solutions related to the game structure, game screens and gameplay as well as on adding new input hardware. Quite a different approach was taken by the scientists, whose suggestions focused on adding well-known scientific models and improving game elements that would aid in teaching physics. Another key observation was that only the scientists group felt compelled by the "physical randomness" entropy generation element, whereas the other two groups ignored it.

The sonification of the pendulum, as a gameplay element that is supposed to assist players in the game task, was commented on only by artists, and the feedback was on the aesthetic nature of the sounds. None of the focus groups used the sonification as a play-aid, even though the groups were instructed to "listen." For example, when the game developer group was shown a setting that produces a high-pitched screeching noise (no-friction on the sun), they did not make the connection to the physical origin of the sounds but rather assumed a software glitch was responsible. The likely cause for this is a lack of documentation or training screens for the players, who are not used to this kind of sonification. The ionospheric sound overlay on the *Gravity Chooser* screen was positively noticed by the game developer as a useful design idea, but the sound canvas did not stand out as an individual element to the other two groups. The subtle nature of this "reality-blending" component may have helped to deepen the immersion for artists and scientists, as they were the two groups which spent the most time experimenting and exploring the gravity models provided by this interface.

Several game elements such as the random processes involved in the gameplay or the gameplay support by the sonification of the pendulum were designed to have a positive effect on the participants of the experiment. However, as the above evaluation indicates, these particular designs seemed to

have very limited impact on the overall game experience or the facilitation of player interactions. How could these observation inform a re-design of an improved version of the game? The entropy extraction element (see section 5.9.1) in the *Pendulum Game* did successfully intellectualize the physical nature of entropy present in the main game process, as the observed discussions with the scientists proved. However, its implementation remained too limited to engage a broader audience since it provided only a "bit" display during gameplay, a status message on the game-over screen, and *Info Link* broadcasts (see section 6.3.5) that were present only in the setup used for the artists group. A re-design of this GPE should consider a play mode that allows for an in-game experiment specifically around the random bit generation (**P13**), ensure that non-interactive content and documentation about the methods used to extract entropy is easily accessible to all players (**P20**, **P21**), and integrate an actual scientific consumer of the random data to emphasize the group-forming activities between players and scientists (**P17**). Conversely, the sonification of the pendulum dynamics, its dependence on the game settings, and the possibility to use it as a play-aid do not result from an overly limited implementation. In my view, the audience could not benefit from this game design element due to a lack of experience with sonifications in general, and their use in computer games in particular. 3D games often feature sophisticated soundscapes that support gameplay, but only when a much broader spectrum of games support subtle, real-time generated audio cues, will players accept the mental challenge such a game element provides **P19**. However, the *Pendulum Game* could have made this feature easier to discover for the player by adding such sound output to the configuration screens (**P1**), by allowing players to substitute the pendulum sonification with traditional game sounds (**P2**), or by adding actual pre-recorded hinge sounds (**P26**) in an effort to make the correlation between the pendulum dynamics and the soundscape more apparent.

In summary, the game physics elements in the *Pendulum Game* have suc-

ceeded in creating novel gameplay modes. This proves, that it is possible to design new game physics elements that are both acceptable to players and advance the state of the art in game physics. The reactions to the games by the groups were partially predictable. Artists seem to have connected more with the aesthetic impact of the game than game developers, who focused on the game's technology, while scientists felt most compelled by the teaching potential of the game. The elements that seem to possess the most obvious potential for a wide adoption of new game physics are the use of physical laws as gameplay rules and the visualization of these phenomena (e.g., the visualized pendulum in the demo). The elements that appear to show the most educational promise are the various modes of reality-blending (e.g., in the gravity chooser), model parameter controls, and the open-ended gameplay without time limits or other competitive constraints. The elements that were not noticed or used by the focus groups include the implementation of hardware randomness elements and the sonification of the pendulum motion. Future research may conduct more fine-grained studies in controlled environments to further this investigation, especially if the goal is to improve usability of the elements.

6.5 Chapter Conclusion

This field study provided new knowledge towards the design of game physics in several ways. Foremost, the study evaluated the proposed new game physics elements that were implemented in the prototype applications against the three primary target groups of this dissertation, which allowed the determination of their effectiveness in game design. Future designs of new game elements can benefit from the study's qualitative assessment of the differences between the three target groups. The comparison informs any further search for additional concrete element possibilities from distinct points of view – artistic, technical, and scientific – since it describes distinct differences in the

interactions of these three target groups with game physics. Thus, this research established good source material for transdisciplinary teams working at the intersection of technology, art and science.

Chapter 7

Conclusion

This dissertation set out to advance current game physics by using transdisciplinary approaches to create value for game developers, artists and scientists. The goals of this study included a demonstration that such *new game physics* can expand creative choices in game design, enable scientifically robust media art and illustrate the use of computer games as a possible education or research tool in physics. The results derived from this novel transdisciplinary approach provide other media researchers with constructive principles that can be used in future investigations involving game physics.

Due to the transdisciplinary nature of the premise, the research process included theoretical and practical methodologies to gather valid evidence. The study initially defined the contemporary meaning of game physics from literature as well as through surveys and interviews with game developers, game players and physicists. Next, a discussion of related concepts from game design and the physical sciences developed a broader concept of game physics. Furthermore, a heuristic categorization of computer games with an associated numerical game physics index was used to perform a quantitative

analysis on game physics over various dimensions. Several theories of play were critically compared and related to game physics in order to extract common design principles for advancing this game design element. Science and game art were also reviewed to extract additional principles, illustrate artistic uses of physics and suggest how game physics could provide value to artists. These intermediate research results were then transferred to practical approaches through the detailed description of several game physics elements as exemplifications. Finally, game libraries and application prototypes were implemented and used in a field study to critically assess the value of these elements for the various target groups. Problems encountered during this practical phase were documented in order to illustrate common challenges in transferring scientific knowledge into the realm of game design or aesthetics.

A goal of this dissertation was to demonstrate ways in which transdisciplinary approaches to game physics provide value in computer game design. I believe that this discourse – a convergence of art, science and technology – needs to use processes that are not only theoretical, but also include a transformative practice and real-world engagement. The game software included in the Appendix and Proof of Practice (Schiffler 2011) is therefore an integral part of such research. These games are also evidence that mixed methodologies can extend or complement purely disciplinary approaches, thereby creating a unique value proposition for game designers.

The extensive definition and analysis of standard game physics presented in chapter 2 shows that game physics is a distinct game design element and often a specialization of one of the base elements (mechanics, story, aesthetics or technology). Three types of standard game physics have been identified: object dynamics simulations, virtual space generation through graphics and sound, and physics content introduced through narratives or characters. An analysis of several games and game technology trends proves that physics simulations in computer games are currently limited with respect to the

breadth of physics fields employed, may not produce realistic physical behavior but rather copy "movie physics," and are almost always simplified to meet some expectation of the players. This phenomenon was described as *pseudo game physics* and is an entertainment-driven design choice by the game developers, which interferes with the needs of educators and scientists. I consulted game developers, game players and physicists through surveys and interviews in order to obtain additional information about these issues. One of the problems encountered during this phase was the reluctance of physicists to participate in the research. While developers and players readily volunteered to discuss the topic and provide feedback, physicists had to overcome significant conceptual barriers to engage with a study involving the mass media of computer games. I believe that the use of *new game physics* may improve such negative perceptions.

In the process of defining standard game physics, I demonstrated that physics could be treated as a broad resource of ideas with a significant cultural impact. Because of the existing limitations of *pseudo game physics*, such a resource can be used in order to extend the concept of game physics by merely introducing additional physics fields. Since it was also shown that physics has significant issues with public perception and is often poorly understood externally, the study concluded that value for the scientists may arise from new game designs. These should consider that *new game physics* can contextualize scientific methods and ideas that are challenging for the public, such as modern physics.

Chapter 3 describes a quantitative analysis of how game physics is used. This analysis was performed in order to estimate the trends in game physics technology and their pervasiveness over time. In order to conduct this analysis, I created a heuristic categorization of computer games with an associated numerical game physics index, an extensive database of game titles, and software methods, to statistically interpret this information. This novel

methodology of analyzing game physics showed that external factors such as technological progress play a key role in how game designers use game physics in commercial games. It was found that game developers are primarily motivated by technological rather than scientific or aesthetic considerations when investing effort into game physics designs. The resulting database is included in Appendix H of this dissertation; it contributes a resource for other game researchers. The game physics index values could provide a useful analytical dimension which can be associated with many existing computer games.

A review of several theories of play was conducted in chapter 4, to define the role of game physics in non-technical ways. This critical comparison provides many mechanisms through which value might be derived from game physics and shows that there are common design principles which can be applied in order to advance this game design element. Several theorists have concluded that computer games have yet to reach their potential as a broad educational tool, and the research indicates that this is in part due to the limited nature of existing game physics. The analysis also points to the following means through which games can be enriched: the addition of new dimensions through game physics, creating "free play" scenarios suitable for adults, providing group-forming activities to bridge disjointed communities, training of game designers to advance physics-based immersion, introducing physics to provide ambivalence and complexity to game rules, and challenging the players mentally rather than physically. During the process of extracting common design principles from the reviewed theories, the study found evidence that game theorists have difficulty even in discussing game physics appropriately. This dissertation offers much-needed *new* material to address this discrepancy.

A review of science and game art in chapter 5 was employed to show that transdisciplinary approaches are useful, since several additional design principles could be extracted. Art games demonstrated that highly intel-

lectual approaches to simple physical laws can produce valuable narratives, and that game design should consider reductive techniques that expose "behaviors" rather than purely focusing on fully-fledged simulations. Artistic uses of physics provided examples of game-like interactions that question the nature of scientific truth, showed the value for the player in expanding the sensory output of games to non-visual media, and explored the dimensional and interchangeable nature of space and time, which is one of the known challenges the general public has with physics. These reviews might become the very evidence that game developers need to be more experimental and that cultural aspects should play a role in game physics in order to further the progress of advancing game design. Although artists and scientists are equally able to be uncomfortable with uncertainty, they still often work in isolated "silos." This study showed that *new game physics* may provide methodologies that can be used to transport physics into games and bridge the works of artists with the research of scientists while at the same time improving game design.

The preceding research results were transferred to practical approaches through the design of game elements in the areas of game mechanics, game story, game aesthetics and game technology. Initially, descriptive examples had a focus on demonstrating value for artists and included elements exploring the ambiguity of time and space through non-constant physical constants, true randomness, and interactivity involving physically correct force fields. However, the bulk of the chapter develops additional exemplary elements in more detail, some of which were actually implemented as part of this dissertation. Topics covered with these elements included the relativistic effects for game time, chaotic motion of pendulum systems, electrostatic field visualizations, the narrative of the discovery of cosmic rays, player avatars derived from chaotic systems, entropy extraction from gameplay, a non-linear narrative browser and various methods for reality blending. The game elements that included software components in the practical phase supported

the premise directly by creating concrete implementation instructions for practitioners that are sufficiently generic to make them reusable in a spectrum of contexts. They show how the design principles might enhance a game, create educational value or improve interactive art installations. Furthermore, a general design framework for GPEs was extracted from the summary of the presented game element designs.

Chapter 6 thus described how a research platform for field studies was created and analyzed. The development process not only illustrated the transdisciplinary approach, but also revealed issues that practitioners can encounter when realizing the elements defined in chapter 5. Although the PTR website and associated HRNG were successfully integrated into two games and used during actual player interactions, the study did not have a large enough audience to generate sufficient data to conclusively validate the proposed entropy generation method. The development of software components for *Pendulum Game* also highlighted two difficulties a game developer may face when integrating scientifically accurate physics. Scientific data, software or background information is often not easily usable for a game designer and generally requires highly domain-specific knowledge or mathematical tools that are not readily accessible during game development. Some physical properties that could provide compelling game rules were found to not have been formally published in the literature, making their discovery and use almost impossible for non-physicists. These issues indicated that a direct involvement of physicists through transdisciplinary game design may be a prerequisite to advancing game physics into new fields or using game physics in interactive art.

The research closed with a field study that evaluated the proposed new game physics elements by letting the three primary target groups of game developers, artists and scientists play the prototypical game application. The novel gameplay modes in the *Pendulum Game* were accepted by all players

and created partially predictable responses. Artists connected the most with the aesthetic impact of the game; game developers had the expected technology focus; and scientists felt most compelled by the teaching potential of the game. The elements that received the most positive feedback by players were the use of physical laws as gameplay rules and the visualizations thereof, the various modes of reality-blending, the ability of model parameter controls to constitute a "virtual lab," and an open-ended gameplay without time-limits or other competitive constraints. The participants did not notice the element of hardware randomness and sonifications – a fact that could be explained through shortcomings in the implementation and a lack of player acceptance. Such limitations may warrant a game element re-design and indicate the need for further studies in these specific areas of game physics in the future. The field study involving the aforementioned groups serves as a seminal reference in transdisciplinary research at the intersection of technology, art and science.

The findings of this dissertation can also be grouped into four main themes. First, it was shown that more research needs to be conducted into game physics; because currently the field is limited with respect to the realism and breadth of physics phenomena that are simulated, and because this limitation negatively impacts the educational and scientific value of game physics. Game developers were found to emphasize the entertainment value of game physics, thinking they satisfy a need for the player. In this context, the very definition they adopt for game physics seems to prevent the development of software (e.g., physics engines) or hardware (i.e., interfaces or devices) for novel applications of physics in games. The evidence proves that game developers are generally not connected in a cross-disciplinary way with artists or physicists during game development. This research suggests that this practice holds back progress in game design, in particular since physics was shown to be a good resource of scientific ideas that can have a significant cultural impact, and because physicists express a need to exploit games to

effectively communicate scientific ideas to the public. Therefore, the study has not only uncovered a new untapped resource for game design but also provided reasons for computer game use outside of entertainment. Based on the analysis of standard game physics, it was found that the entertainment industry controls game content and commonly pushes for physically incorrect simulations of reality in games, much as it does for movies ("movie physics"). I introduced the term *pseudo game physics* to identify this design style, and showed that it may cause negative side effects for the players. Until now, it has hardly been studied how the introduction of pseudo physics in games and other media can cause an impact on users. Future research should be conducted to study the mechanisms and possibly harmful effects of such types of game physics on game players.

Second, the study showed that additional guidelines are needed to advance the field of game physics design and presented a list of *principles* for this purpose. These principles were generated by adapting ideas that originate from the various transdisciplinary sources discussed in the text for the purpose of transferring physics into game design in a scientifically sound way. For example, one of the principles stated that in order to help establish a social discourse involving science, game developers should seek precision or at least evaluate it, because without precision game physics cannot be used in a scientific context. I established that the definition of such principles should enable knowledge transfer and encourages a more theoretical analysis into game physics. On a practical level, it allowed the development of prototypical game elements that expand on the state of the art in game physics design. The application of these principles was shown to generate a range of positive effects on the user, including an improved acceptance and learning of physical concepts. Foremost, however, these principles helped to create a toolset and language for transdisciplinary teams involved in game development – a design framework for GPEs. Future research many expand on this list of guiding principles for game physics design.

Third, I applied the aforementioned principles and proposed several *new game physics elements* to demonstrate that they can add value to the three groups of content developers targeted by this research. It was shown that the value of these elements for game developers is derived from their ability to improve existing game design or create new physics-based gameplay rules and aesthetics. Perhaps developers may also use the principles directly to create innovative game design ideas or improve the potential to educate in serious games. As was shown through my proof of practice, new game physics elements can enhanced gameplay, created new forms of interactivity and improved the teaching effectiveness of games. The value potentials for artists are far more complex. As the study showed, the use of game physics does not need to modify the artist's original intent, but rather augment it, for example by transforming a non-interactive work into an interactive one. If artists used game physics, according to the principles presented, it would open up their works to new audiences such as game developers and scientists. It was described that value is created when art is enabled through these elements to act as a catalyst, which brings science to the public. It is this ability of new game physics to improve the communications between the science community and the public that creates the primary value for scientists. New game physics can facilitate the breakdown of conceptual barriers that prevent many physicists from engaging with mass media such as computer games. In addition, new game physics can offer the public insights into current debates in physics in novel and engaging ways. Future research should make these elements more accessible to these three communities and develop modes for broader dissemination, such as via the Internet. Another area could expand on the question of whether such new game physics can be used to conduct actual scientific research.

I assert that the novel results presented in this research enable the reader to design better game physics. The development of a new, transdisciplinary methodology had to be made, in order to apply the evidence arising from the

theoretical and quantitative analysis. The game physics examples based on this work demonstrate that one *can* successfully extend the existing, standard game physics practice towards the proposed new game physics ideas. The actual prototypes allow others to directly witness the described principles in practice and a further dissemination of the evidence presented in this study should raise awareness about the potential of *new game physics* across all the disciplines involved.

In conclusion, this dissertation provides important contributions to new knowledge in the fields of science, art and game design; and any future work of transdisciplinary teams in computer game design or media art should consider the results of this research to realize the value that game physics can provide to the final outcome.

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Glossary

2.5D is a term to describe either a graphical projection technique which causes a scene to appear three-dimensional (3D), or a gameplay restriction of a 3D game to a two-dimensional plane. 16, 30

2D two-dimensional. 27, 35, 96, 97, 146, 157, 176, 184, 195, 219, 229, 245, 254, 257

3D three-dimensional. 14, 16, 17, 28, 35, 37, 54, 62, 75, 93, 95–97, 99, 104, 107, 109, 126, 128, 184, 187, 213, 215, 218, 229, 249, 274

activation cycle refers to the brains' natural response to stimuli in the sequence of activation and deactivation of neuronal activity; influences learning and behavior. 133, 143

affordances describe the qualities of an object, or an environment, that allow an individual to perform actions that are physically available (*action possibilities*) or that the actor is aware of (*perceived action possibilities*). 140

AI Artificial Intelligence. 27, 34, 63

aleatoric music is music in which some element of the composition is left to chance, the term being derived from the Latin word *alea*, meaning "dice". 193

allegorical is a term derived from the Greek word *allos*, or "other" and describes an expression in which the figurative mode of representation conveys a meaning other than the literal meaning. 138

Alpha emitter is a radioactive substance that decays by emitting alpha particles. 240

AMLS Automated Multi-Level Sub-structuring. 228

antagonism is the act or feeling of hostility that results in active resistance, opposition, or contentiousness. 138

API Application Programming Interface. 17, 241, 242, 249

AR Augmented Reality. 139

avatar is a term that describes the computer user's representation as a 3D model, 2D image or textual username and may appear in a wide range of applications such as virtual worlds, computer games or social networks. 12, 14, 16, 19, 43, 95, 97, 157, 213–217

Bremsstrahlung is the electromagnetic radiation produced by the acceleration or deceleration of a charged particle, such as the radiation of electrons stopping in matter. 212

buoyancy force is the force exerted by a fluid, gas or plasma, that opposes an object's weight. 255

calculus is a branch of mathematics which is concerned with the study of how functions change when their inputs change and covers differentiation as well as integration methods. 58

chi-square test is a statistical hypothesis test in which the samples assume a chi-square distribution defined by the sum of the squares of independent, standard normal random variables with k degrees of freedom. 245

chunking is a term in cognitive psychology introduced by George A. Miller (1956) which refers to strategies for making more efficient use of short-term memory. Chunking refers to a unit of perception and meaning or a learning mechanism. 143, 144

clock drift refers to a phenomenon where one clock does not run at the exact same speed compared to another clock, causing the measured time to "drift" compared to the actual or reference time. 240

collision response is the description for the change in motion of solid bodies following a collision or contact. 19, 20

Compton scattering is the inelastic scattering of photons in matter and results in a decrease in energy of the photon, ejection of an electron and ionization of the atom. 212

cosmic ray primaries are stable charged particles such as protons that have been accelerated to large energies by astrophysical sources and originate from interstellar and intergalactic space. 210

CPU Central Processing Unit. 28, 29, 54, 80, 240, 246

dichotomy is any splitting of a whole into two jointly exhaustive but mutually exclusive parts. 10, 74, 166

diegesis is the telling of a story by a narrator, such as describing a fictional world or recounting of events. 158

DirectX is a collection of application programming interfaces published by Microsoft for handling tasks related to multimedia, especially game programming and video, on PC platforms. 17, 246

DLP Digital Light Processing. 267

electroscope is an early scientific instrument used to detect electric charge by observing the motion of test objects in an electrostatic field. 209, 210

embodiment is a position in cognitive science and the philosophy of mind that emphasizes the role that the body plays in shaping the mind. 152

FAC Free Air Correction. 230

FPS First-Person Shooter. 43, 49, 96, 149

fractal is "a rough or fragmented geometric shape that can be split into parts, each of which is (at least approximately) a reduced-size copy of the whole" (Mandelbrot, 1982). 257, 258

FSM Finite-State Machine. 140–142, 222, 223

game worlds are self-consistent fictional settings constructed inside a computer game which usually contains its own background elements, including history and geography based directly or indirectly on our own universe, fantasy or science fiction elements as well as other derived background elements. 126, 128, 131, 153

geodesy is a scientific discipline with a focus on the measurement and representation of the Earth as a 3D time-varying model describing gravitational fields and other dynamical phenomena. 229, 232, 236

Gestalt Psychology is a theory of mind that was formed in the beginning of the 20th century to redefine the approach to psychological research and proposes that the operational principle of the brain is holistic, parallel, and analog, with self-organizing tendencies and the premise that the whole is greater than the sum of its parts. 131

GPS Global Position System. 200

GPU Graphics Processing Unit. 16, 18, 29, 81, 219, 220, 246, 261

hardware interrupt refers to an asynchronous signal in a physical computer which indicates the need for attention and causes the processor to save its state of execution and begin execution of an interrupt handler (synchronous event in software). 240

HCI Human-computer Interaction. 189

heuristic refers to an experience-based technique for problem-solving and discovery, in order to identify an optimal solution quickly. 4, 82, 277

HLSL High-Level Shader Language. 261

HRNG Hardware Random Number Generator. 193, 194, 222, 225–228, 239–241, 244, 246, 255, 260, 282

HTML stands for "HyperText Markup Language" and is the predominant markup language for Web pages. 100–102

HUD Heads-Up Display. 39

hydrostatic lubrication is a technique employed to reduce wear of two surfaces in close proximity, and moving relative to each other, where a liquid lubricant is applied with external pressure in order to maintain a fluid lubricant film. 257

hypocycloidal is the motion of a point fixed on a circle that rolls on the inside circumference of a fixed circle. 257

ICGEM International Centre for Global Earth Models. 250, 251

iconic is an attribute of an object or process derived from the study of images using a critical "reading" of imagery that attempts to explore social and cultural values and significance for a particular culture or time. 143, 171, 176, 213

immersion is a term to describe a state where one ceases to be aware of the physical self, frequently accompanied by intense focus, distorted sense of time and effortless action. The term is not used consistently and fragmented into various sub-categories depending on the type of immersion (psychological, spatial, narrative, cognitive, strategic). 167, 169, 207, 211, 228, 229

LAN Local Area Network. 247, 263, 267

LCD Liquid Crystal Display. 268

Legendre polynomials are solutions to the Legendre differential equation, an ordinary differential equation that is frequently encountered in physics and other technical fields. 250

ludic is a term derived from Latin *ludus* meaning play, playful or fun; refers to any philosophy where play is the prime purpose of life. 123

machinima is the use of real-time graphics capabilities of game engines to generate computer animation. 172

magnetosphere is a region of space around a celestial body whose shape is determined by its internal magnetic field; it forms when a stream of charged particles, such as the solar wind, interacts with the field. 262

MHD magnetohydrodynamics. 196, 197

MIPS Million instructions per second. 18

MMOG Massively Multi-player Online Game. 34, 221

MMORPG Massively Multi-player Online Role-Playing Game. 52, 95, 99, 211

mod is a term applied to computer games to describe modifications made to a game without changing the original game software; may include the addition or change of items, weapons, characters, enemies, models, textures, levels, story lines, music, and game modes. 172–174

MySQL is an open source relational database management system (RDBMS) that runs as a server providing multi-user access to a number of databases. 100, 241

NPC Non-Player Character. 63

NSF National Science Foundation. 34

nuclear decay is the process by which an unstable atomic nucleus loses energy by emitting ionizing particles and radiation. 240

OOP Object Oriented Programming. 159

OpenGL is a standard specification defining a cross-language, cross-platform API for writing applications that produce 2D and 3D computer graphics. 17

PA probabilistic automata. 141, 223

Pair production refers to the creation of an elementary particle and its antiparticle, usually from a photon. 212

phase space is a space in which all possible states of a system are represented as a unique point. In mechanical systems, the phase space dimensions are usually position and momentum. 206

phenomenology is a term in psychology that refers to the subjective experience of a person or a self, which is not directly observable by an external observer. The experience may be of perceptual, emotional, cognitive, or conative nature. 124

PHP PHP: Hypertext Preprocessor. 241

plasma is a state of matter in which a certain portion or all of the particles in a gas are ionized into positive ions and negative electrons. viii, 197, 262

plasma wave is an electromagnetic or electrostatic perturbation in the quasi-neutral, electrically conductive fluid of a plasma which propagates in a periodically repeating fashion. 262

platformer (or platform game) is a computer game genre that originated in the early 1980s in which jumping on platforms via a jump button is the core part of the gameplay. 62, 66, 96, 97, 176

PRNG Pseudo Random Number Generator. 126, 142, 193, 221–223, 225, 228, 241, 244, 246

QFA quantum finite automata. 141, 223

quantum optical effect is a property of light caused by the quantized nature of photons. 240

resistor is a two-terminal electronic component designed to drop the voltage of the current as it flows across the terminals. 240

Reynolds number is a dimensionless value used in fluid dynamics to describe the ratio of inertial forces to viscous forces of a fluid, gas or plasma that is in relative motion to a surface. 255

rote learning is a learning technique that avoids understanding of a subject but instead focuses on memorization through the practice of repetition; prevalent in many religious schools throughout the world

and generally considered a useful learning technique in language training, mathematics, and music. 126

RPG Role-Playing Game. 62

satirical is a term describing an expression whose defining feature is irony or sarcasm, usually meant to be funny; can be found in many artistic forms of expression, including literature, plays, commentary, and media such as song lyrics. 138

scripting refers to the generation of programs (scripts) using a programming language that allows control of one or more software applications and that is interpreted rather than compiled. 13

shot noise is a type of electronic noise that occurs when the number of electrons in a circuit is small enough to give rise to detectable statistical fluctuations in a measurement. 240

SLAC Stanford Linear Accelerator. 181

sonichima is music made by playing an existing game. 172

sonification is the use of non-speech audio to convey information or perceptualize data. 180, 181, 185, 248, 262, 273–275, 283

sonoluminescence is the effect of emission of light from imploding bubbles in a liquid which has been excited by sound waves. 179–181

spherical harmonics expansion is the representation of a function in terms of spherical harmonics, which are the angular portion of a set of solutions to Laplace's equation in a spherical coordinate system. 250

SQL Structured Query Language. 102, 244

SR Special Relativity. 199

steady state is the state of a system once its properties are not changing in time. 19

Stokes' drag is the linear viscous resistance when an object moves through a fluid, gas or plasma at relatively slow speeds and in absence of turbulence. 255

Stribeck curve is a graph describing the friction forces between two materials; it was named after the German engineer R. Stribeck whose experimental charts first described this relationship. 272

systemic bias are external influences that may affect the accuracy of statistical measurements. 226

TE Turing Event. 229

tribology is the science of interacting surfaces in relative motion; includes the study of friction, lubrication and wear. 248

tripartite is a term meaning "composed of" or "split into" three parts; or refers to three parties. 153

UDP User Datagram Protocol. 263

URL Uniform Resource Locator. 242, 246, 259, 264, 265

VLF Very Low Frequency. 262

voluntary is a term used to describe a process of "doing something for one's own free will" (such as volunteering or playing games); linked to the psychological theory of activity which includes topics such as concept formation in children, voluntary and involuntary memory, voluntary behavior, and reasoning. 120, 121

VR Virtual Reality. viii, 13, 16, 32, 34, 42, 54, 55, 72, 93, 95, 99, 107, 126, 131, 179, 183

Web service is a software system designed to support a method of machine-to-machine communication over a network through the description of its interface in a machine-processable format. 6, 226, 228, 239, 240, 243, 244, 246, 251, 259, 260, 266

XML Extensible Markup Language. 263

Zener breakdown is a phenomenon that can occur in the semiconducting materials of Zener diodes when the reverse bias breakdown voltage is exceeded, allowing for high current flow. The flow is due to an effect called avalanche breakdown, when the carriers in the transition region of the diode are accelerated by the electric field to energies sufficient to free electron-hole pairs via collisions with bond electrons. 240

Appendix

The appendix document can be found on the *Proof of Practice* DVD entitled "Appendices, game executables, source code and supporting files."

Table of Contents

A. Personal Motivation

B. Physics in Context

C. Examples of Game Physics

D. Game Categories

E. Interviews

F. Surveys

G. Science Art Reviews

H. Source Code

I. Video Documentation

Proof of Practice