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Calculating conceptions of natural phenomena: an archaeology of fluid simulation software

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Abstract

Already since the 1960s, the field of computer science has been concerned with realistically simulating our natural world. The complex and unpredictable behavior characterizing natural phenomena like splashing waters and whirling fires has been an important topic of research for both the natural sciences, as well as the visual effects industry. Building on similar mathematical concepts, these fields try to capture and predict our natural environment through computation. Where the natural sciences are concerned with grasping the laws of nature, the visual effects industry aims to achieve realistic visualizations, independent from physical laws. This thesis looks at fluid simulation software, used for the visualization of phenomena like water, fire, and air, through a media archaeological approach to interpret computational systems. Such an approach, as formulated by Wardrip-Fruin in *Media Archaeology* (2011), aims to 'dig out' the operational and ideological frameworks embedded in the structures and processes of computation. Using a theoretical framework ranging from media studies, philosophy of science and technology, phenomenology, and elemental theory, this thesis points towards a tension between the mathematical descriptions of water, fire, and air, and understandings of these phenomena as offered through elemental theory. Engaging with this tension shows how fluid simulation technology is steered by a rational, and instrumentalizing way of understanding the natural environment, which influences its possible usage and output. By comparing simulation with technologies for recording or sensing, it is shown that the goal of achieving hyperrealism in the development of fluid simulation software enforces visualizations of natural phenomena based on a "film-based image" of reality. Accordingly, this thesis proposes to use the work by philosopher Gaston Bachelard, and specifically the notions of 'phenomenotechnique' and 'material imagination', as a framework for the study of (fluid) simulation software, as it offers an understanding of the technology as inherently fictional and speculative, allowing for a process of creation that can destabilize its tendency for realism and a notion of computational visualization as objectively describing reality.

Contents

Introduction

Ever since the 1960s, the field of computer graphics science has been concerned with ways of simulating our natural world through code. The realistic visualization of natural phenomena like water, wind, fire and smoke has been a renowned challenge in the computer sciences because of the particularly complex and unpredictable behavior that characterizes these phenomena.[1] Since the 1980s, the increasing reliance on computer generated imagery in the entertainment industry has motivated computer graphics researchers to extensively study the scientific field of Computational Fluid Dynamics (CFD), a research-track originating from the 1940s, managed by US federal funding and its military-industrial complex.[2] The algorithms developed for the scientific study of fluid flows proved useful for adaptation into software tools for the animation of splashing waters and whirling fires. This resulted in the continuing development of fluid simulation software. Even though this technology is primarily designed for the visual animation of natural phenomena, the mathematical concepts that structure its underlying algorithms are based on the same principles as its scientific precursors used to predict unpredictable systems like weather forecasts and financial markets.[3] However, what clearly distinguishes the technology for fluid simulation, is that its algorithms no longer need to follow the accurate physics that define the behaviour of dynamic phenomena in real life environments.[4] Rather, these nonlinear simulations of nature are primarily modelled to occur accurate according to human perception.[5] As mentioned by media historian Jordan Gowanlock in *Animating Unpredictable Effects: Nonlinearity in Hollywood's R&D Complex* (2021), through a close relationship with the field of engineering, computer visualization and animation techniques share a similar way of understanding contingency and seeking to control it. The

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[1] Ronald Fedkiw, "Simulating Natural Phenomena," in *Geometric Level Set Methods in Imaging, Vision, and Graphics*, ed. Stanley Osher and Nikos Paragios (Berlin, Heidelberg: Springer-Verlag, 2003), 461.

[2] Jordan Gowanlock *Animating Unpredictable Effects: Nonlinearity in Hollywood's R&D Complex* (London: Palgrave Macmillan, 2021), 27-28.

[3] Jordan Gowanlock, *Animating Unpredictable Effects*, vii.

[4] Donald P. Greenberg, "A Framework For Realistic Image Synthesis," *Communications of the ACM* 42, no. 8 (August 1999): 44, https://doi.org/10.1145/310930.310970.

[5] Jos Stam, "Stable Fluids," in *ACM SIGGRAPH 2004 Course Notes*, ed. Oliver Deusen, David S. Ebert, Ron Fedkiw, F. Kenton Musgrave, Przemyslaw Prusinkiewicz, Doug Roble, Jos Stam and Jerry Tessendorf (New York, NY: Association for Computing Machinery, 2004), 4-1. https://doi.org/10.1145/1103900.1103932.

technologies for nonlinear system simulation, used to mediate concepts like risk and control in disciplines as climate science, geology, management science, and financial mathematics, embed a way of seeing the material world through a notion of instrumentalization and rationalization.[6] In this work, Gowanlock connects the development history of nonlinear simulation with the way in which society has come to think of simulation as point of reference for understanding and managing unpredictability. The author discusses how the usage of nonlinear simulation in the visual effects industry seemingly caused a collapse of the differences between simulation and reality. Hyperreal visualizations of complex, natural patterns, and phenomena like ocean waves, branching trees or mountains made through simulation, enforced an understanding of simulation as creating natural life. Nature's emergent processes would conform to the computational logic used to imitate it, rather than the other way around.[7] The author explains nonlinear simulation as a valuable technology for visual effects and animation as it offers great control for the animator over the complex and unpredictable movements of phenomena like ocean waves or fires, a type of control that is impossible to achieve using methods like recording. However, Gowanlock illustrates that this technology is also more representationally restrictive. According to the author, its development has been steered by a rationalizing way of understanding the world and the aim to creating tools to master unpredictability through computational science.[8]

Following this notion of nonlinear simulation as a tool to manage and control the unpredictable, this thesis turns specifically to fluid simulation software to make visible how this technology, rooted in the military-industrial complex, enforces visualizations of natural phenomena restricted by a paradigm of human-control over- and instrumentalization of nature. As Jussi Parikka argues in *A Geology of Media* (2015), our relations with the earth are mediated through technologies of visualization and calculation. Therefore, it is through media that we can understand earth as object for cognitive, practical, and affective relations.[9] Fluid simulations have become omnipresent in contemporary cinema and entertainment, and often

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[6] Jordan Gowanlock, *Animating Unpredictable Effects*, 2-5.

[7] Jordan Gowanlock, *Animating Unpredictable Effects*, 152-153.

[8] Jordan Gowanlock, *Animating Unpredictable Effects*, 148.

[9] Jussi Parikka, *A Geology of Media* (Minneapolis, London: University of Minnesota Press, 2015), 12.

we might not be able to distinguish the computational simulation from live footage. Nevertheless, as will be discussed in this thesis, the two are inherently different. Instead of representing nature through methods of recording or sensing, the computational simulation visualizes nature through the construction of a model. These models work in favour of simulating the mechanisms behind real-world phenomena based on mathematical descriptions of reality as dependent on human perception and understanding.[10] By addressing the simulation of natural phenomena, specifically the elements of water, air, and fire, this thesis points towards a tension between these mathematical descriptions of nature, and discourses on these phenomena found in philosophy and elemental theory. For example, works like *Elemental Ecocriticism: Thinking with Earth, Air, Water and Fire* (2015) edited by Jeffrey Jerome Cohen and Lowell Duckert, advocate for a thinking in 'elemental terms' to make visible how earth, water, wind, and fire primarily exists in human-knowable form. This is part of way of thinking about the material world as mere resource to be picked and used by humans. By understanding the elements as exceeding our humanly knowable scale and embracing their dynamism and complexity, elemental ecocriticism aims to make visible how the way that we think about- and describe the elements matters in terms of their ecological significance as well as their effects on (material) imagination.[11] In the 1940s, philosopher Gaston Bachelard conceptualized such thinking with the elements through notions of material imagination in works as *La psychanalyse du feu* (1938) / *The Psychoanalysis of Fire* (1964), *L'eau et les rêves* (1942) /*Water and Dreams* (1983), *L'air et les songes* (1943) / *Air and Dreams* (1988), *La terre et les rêveries de la volonté* (1948) / *Earth and Reveries of Will* (2002) and *La terre et les rêveries du repos* (1948) / *Earth and Reveries of Repose* (2011). Following Bachelard, the elements of fire, water, air, and earth specifically confront us with notions of indeterminacy and ambiguity. The elements serve as the ingredients for an imaginative conception of the material universe which, according to Bachelard, becomes present in imaginations and experiences of nature in literary texts or daydreams. These imaginative conceptions of the elements should be considered

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[10] Jordan Gowanlock, *Animating Unpredictable Effects,* 7.

[11] Jeffrey Jerome Cohen and Lowell Duckert, ed., *Elemental ecocriticism: Thinking with Earth, Air, Water, and Fire* (Minneapolis: University of Minnesota Press, 2015), 314-315.

realities of the natural elements by themselves and studying them as such can afford a deeper understanding of our human existence in relation to the natural environment.[12] Such elemental philosophy tries to make visible specific affordances of the elements of water, fire, air and earth and the possible knowledges found in their unpredictability. Moreover, these works specifically link the elements to human imagination as both forces that are restless, ever composing of new things and therewith are capable of challenging narratives. The abovementioned works question the narratives created by modern science that use theories of capture and disclosure, which enforce an understanding of matter as something existing outside of us, instead of humans being embedded within the material world.[13] According to an elemental philosophy, the way we think-, write about and visualize the elements is a matter of concern. As Lowell Duckert argues, the way in which we narrate stories can shape earth/s to come.[14]

Simulations generally model complex physical systems to test the validity of underlying theories. Therefore, to build models and running a simulation is to attempt a new way of understanding the world.[15] Looking at fluid simulation technology, therefore, can shed light on the underlying theories that create visualizations of natural processes and phenomena and therewith play a part in the way in which we understand our natural environment. As a tool based on the science for prediction and control of unpredictable systems, this thesis questions the possibility of stimulating imaginative use and notions of ambiguity through fluid simulation software. Importantly, this thesis not only aims to study how fluids simulation negotiates uncertainty, but also to indicate how uncertainty and ambiguity can effectively be used to engage with fluid simulation as technology for speculation and imagination, rather than realistic representation. As Miguel Carvalhais argues in *Art and Computation* (2022), computational media can be understood as ‘hyperreal simulacra’ that do not necessarily bear a relationship to an external reality. Here, computational media differ from classical media methods of recording

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[12] Yanping Gao, “Between Matter and Hand: On Gaston Bachelard's Theory of Material Imagination,” *Journal of Comparative Literature and Aesthetics* 42, no. 1 (Spring 2019): 80, https://issuu.com/jclaindia/docs/jcla_spring_2019__vol._42__no._1__pdf.

[13] Jeffrey Jerome Cohen and Lowell Duckert, ed., *Elemental ecocriticism: Thinking with Earth, Air, Water, and Fire*. 299-301.

[14] Jeffrey Jerome Cohen and Lowell Duckert, ed., *Elemental ecocriticism: Thinking with Earth, Air, Water, and Fire*, 239.

[15] Jordan Gowanlock, *Animating Unpredictable Effects,* 41-42.

and sensing, as they become “a new reality that is neither descriptive nor prescriptive, but that "inscribes the world", by adding to it and transforming it.”[16] Therefore, to understand and analyze computational media, an epistemology of “knowing how” in addition to the scientific “knowing that” is needed.[17] By analyzing fluid simulation software through its mathematical concepts and technical properties, this thesis aims to contribute to this current research into computational media and its specific ways of embedding- and producing knowledge.

Analysing fluid simulations: combining technical-, historical- and philosophical frameworks

To properly engage with the technicalities of software as object of study within the humanities, the framework of media archaeology as described by Jussi Parikka in *What is Media Archaeology?* (2012), as well as *Media Archaeology: Approaches, Applications and Implications* (2011), ed. by Parikka and Erkki Huhtamo, seems effective. In *What is Media Archaeology?*, Parikka explains that media archaeology is centred around the idea of experimenting with alternative and peculiar ideas embedded in technology, or engaging with types of technology that might have failed to become mainstream, or part of a public discourse. To do so, media archaeology applies a practice that tries to ‘excavate’ the past in terms of analysing outdated, turned-obsolete, or unnoticeable technologies to help better understand the present and future of media. However, according to the authors of abovementioned works, to excavate technologies as such, a combination of methods is needed ranging from the academic- to the artistic.[18] Accordingly, a practice of media archaeology is not fixed. Rather, it often combines a variety of methods and practices depending on the technology or media of study. In this thesis, this variety is mostly reflected in the way that it deals with computational science and mathematical concepts, as well as elemental philosophy. Therewith, this method also aims to indicate the value of blurring distinctions between the computational sciences and the humanities. Academic disciplines that are often still labelled as ‘hard’- and ‘soft sciences’,

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[16] Miguel Carvalhais, *Art and Computation* (Rotterdam: V2_ Publishing, 2022), 42-44.

[17] Miguel Carvalhais, *Art and Computation*, 25.

[18] Jussi Parikka, *What is Media Archaeology?* (Cambridge: Polity Press, 2012), 1-2.

carrying assumptions on their supposed level of objectivity.[19] Specifically when dealing with software as topic of study, a combination of media studies, computational science, history and philosophy of science and technology and visual culture are argued to be important as software is both a technical, as well as a cultural and visual medium. Software is an intangible set of operating information used to perform computation, which becomes visible by means of an interface. Software can be studied through its source code, but the way in which a program performs only becomes evident when this code is running. The perceived output, however, does not necessarily bear a clear referential relationship to the code making software something quite obscured. Nevertheless, something that many types of software share, is that their languages are based on abstractions of antecedent programming languages. Therefore, each programming language can be considered an indication of the designs and specifications of earlier variations. Current software contains information about the needs of preceding software. A media archaeological approach to computation and software therefore seems highly applicable as it aims to 'dig out' those preceding ideologies that have shaped current technologies and media devices. Software is not only the final program used by its users, rather it encompasses the complete process of development ideas, technical creation, product outcome and the following further development. Accordingly, software contains information about the outside world in terms of what type of problems needed solving and what new ideas emerged when interacting with it during different periods in time.[20] Therefore, it is argued that software can be seen as to embody knowledge about a relation between society and computation.

To analyze fluid simulation software as a body of knowledge, this thesis specifically uses a media archaeological approach to interpret computational systems as was formulated by Noah Wardrip-Fruin in *Media Archaeology* (2011). According to Wardrip-Fruin, the operational and ideological frameworks of digital media are much more visible in the structures that define

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[19] Steven Shapin, "Hard science, soft science: A political history of a disciplinary array," *History of Science* 60, no. 3 (June 2022): 327-328, https://doi-org.proxy.library.uu.nl/10.1177/00732753221094739.

[20] Peter Freeman, "Software Development Systems," *Computers and People* 36, no. 9-10 (Sept. – Oct. 1987): 13.

their movements than in its states or outputs.[21] The author argues that as processes are crucial to digital media, an archaeology of such media must move beyond what is mostly done through historical discussions of such media, and begin to grapple with the ideas embedded in digital media systems themselves.[22] Accordingly, studying fluid simulation software requires specific methods to interpret its computational system. These methods include analysing its data and processes, rather than focussing its outputs (e.g. a specific CGI film using fluid simulation). Therefore, the mathematical concepts and numerical properties that structure the software algorithms are considered. To do so, this thesis studies archival material from the Association for Computing Machinery's Special Interest Group on Graphics and Interactive Techniques (ACM SIGGRAPH) on the development of fluid simulation software.[23] SIGGRAPH is one of the most important research organizations in the field of computer graphics and its annual conference has been significant in shaping the direction of the technologies produced by academic scholars as well as the media industry since the 1970s. Therefore, the SIGGRAPH archive material can show how specific technological applications took shape over time and what type of adaptations were sought after in associated institutions and businesses.[24] Specifically, the SIGGRAPH'04 course manual "The Elements of Nature: Interactive and Realistic Techniques," edited by Oliver Deusen (et al.) offers a multitude of research papers discussing simulation algorithms for the computer visualization of (in order of appearance in the manual) water, fire and smoke, air, and earth. Written in 2004, the manual reflects on previous methods for the realistic visualization of the elements of nature by pointing out weaknesses of these methods and how these have been adjusted and improved. Interestingly, the papers discuss the elements of water, wind/clouds, smoke, and fire extensively in separate chapters. The material offers insights in the interdisciplinary efforts needed between the field of engineering, natural sciences, and arts to visualize nature, which proves useful to question

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[21] Noah Wardrip-Fruin, "Digital Media Archaeology: Interpreting Computational Processes," in *Media Archaeology: Approaches, Applications and Implications*, ed. Erkki Huhtamo and Jussi Parikka (Berkeley, Los Angeles, and London: University of California Press, 2011), 302.

[22] Noah Wardrip-Fruin, "Digital Media Archaeology: Interpreting Computational Processes," 320.

[23] "SIGGRAPH: Special Interest Group on Computer Graphics," SIGGRAPH Home, ACM Digital Library, accessed December 8, 2023, https://dl.acm.org/sig/siggraph.

[24] Jordan Gowanlock, *Animating Unpredictable Effects,* 57-58.

the usage of similar tools for scientific purposes as well as for artistic imagination. The documents give insight in a particular discussion between science and art which offers an understanding of the intended- and non-intended usages of this technology. Moreover, the material indicates the continuing usage of similar algorithms for current visualizations of natural phenomena. The analysis of this manual focusses specifically on the research questions and discourses found in the included research papers dealing with the development of the software; what was needed in technical terms to adjust these simulation algorithms for purposes of visualization, and through which properties are phenomena as water, air and fire translated into computation? As will be argued, the properties used to visualize natural phenomena as computational objects offers insight in a particular way of understanding the world through simulation where things non-numerical are translated and into mathematically controllable object.

The first chapter answers the sub-question of how a practice of software archaeology offer insights in the ideological frameworks that structure research and development in the computational sciences (e.g. SIGGRAPH) and therewith shape possible processes of computational visualization? To do so, this chapter engages with the technical properties of fluid simulation through an analysis of the SIGGRAPH material in combination with the work *Fluid Simulation for Computer Graphics* (2016) by Robert Bridson. Bridson's work offers a general overview of the mathematical concepts that structure basic fluids equations which helps to make sense of the specific adjustments made to this technology to successfully visualize water, fire, and air. The exchange between the field of engineering and animation in terms of physical simulation is made apparent in both these works and can help to understand the travel of simulation algorithms from the field of military- and industrial research, into the visual effects industry. Accordingly, the first chapter also engages with notions of nonlinear- and physical simulation to better understand the origins of fluid simulation technology and its specific affordances. For this purpose, *Animating Unpredictable Effects: Nonlinearity in Hollywood's R&D Complex* is an important source. The work by Gowanlock offers a historical overview of the development of nonlinear system simulations and specifically addresses the influence of the visual effects industry, as well as the US military-industrial complex on research and development in this field. This work proves relevant for this thesis, since it explains how these algorithms, developed for purposes of prediction, management, and control, were adapted in the visual effects industry in favour of controlling visual output. Importantly, Gowanlock argues how specific epistemic frames can be found embedded in these tools, shaping their possible usage. Understanding nonlinear simulation and the basic fluid equations allows for the specific analysis of the similarities and differences between the simulation of each, specific natural phenomenon. Therefore, the first chapter elaborates on the technicalities and characteristics of computational waters, fire, and air. This analysis provides insight into an interesting trade-off in this technology between the laws of physics, artistic intervention, and the ability to control visual output. Gowanlock similarly discusses the interdisciplinary efforts needed between engineering, animation, and the arts, for the development of nonlinear simulations. Therewith, this chapter offer insights in some of the ideological frameworks that structure research and development in the computational sciences that shape the possible processes of- and usages for computational visualization.

The second chapter engages with the sub-questions of how technologies for simulation mediate understandings of reality different from classical media technologies for representation, like methods of recording or sensing? The chapter specifically addresses how simulation differs from other media technologies in the way that they operate *as* a reality, rather than creating images *of* reality. Gowanlock approaches nonlinear simulations as speculative versions of scientific simulations. This notion will be used to argue how simulations of natural phenomena should not merely be understood as realistic representations, but as constructed models that represent a specific way of thinking about our natural world, and specific methods of understanding it. Moreover, the work *Art and Computation* (2022) by Miguel Carvalhais similarly argues that computational media should be understood as inherently different from classical media for representation. The ideas of both these authors on simulating reality will be applied to fluid simulations as covering a kind of middle-ground between a scientific reality built on mathematical law and the speculation and imagination brought in by artistic use. Additionally, this chapter engages with the goal of achieving realism that structures the research agenda of many techniques for visualization and animation. Understanding how the design of fluid simulation technology steers towards 'realistic' usage, can provide insight into how fluid simulations might influence our conceptions of our natural environments.

The third chapter answers the question of how the mathematical concepts structuring fluid simulations erase complexity and ambiguity from computational visualizations of water, fire, and air. Therewith, the chapter aims to make visible a tension between the conceptions of our natural environments embedded in fluid simulation technology and ideas on nature and its phenomena as offered by elemental ecocriticism and philosophy. The purpose of this chapter is to discuss how the specific technicalities of simulation enforce an understanding of nature that erases complexity and ambiguity which, following elemental philosophy, seem specifically important for our relationship with the earth and the nonhuman. The conceptualization of materiality that does not center around the human, as offered by *Elemental Ecocriticism* (2015), is used to analyze, and question the discussed mathematical concepts and properties that structure fluid simulation technology. The work offers an engagement with ecological thought through the elements of water, fire, and air. Moreover, the essays in this work address how knowledge can be found in the ambiguity and unpredictability of the natural elements, something this chapter argues to be eliminated when nature is described through computational simulation. *Elemental Ecocriticism* (2015) also offers a counterview to the idea of the world as resource, to be picked and used by the human. These notions will be used in this thesis to indicate the importance of studying *how* we visualize natural phenomena through computation which, as will be argued, is grounded in an understanding of natural phenomena as resource and object to be observed by humans as-if standing outside of these environments instead of being embedded within. Lastly, elemental theory is used to offer insight in the importance of imagination in favour of a decentralization of the human. Therewith, this chapter aims to indicate what type of knowledge on natural phenomena is lost when translated into a metric, computational object, and how this can give way for the usage of fluid simulation as tool for stimulating imagination and speculation.

The last chapter answers the sub-question of how the notions of 'material imagination' and 'phenomenotechnique', as formulated by Gaston Bachelard in the author's writing on the elements offer an effective framework for the usage of fluid simulation as tool for imagination and speculation? This final chapter uses the notions of 'material imagination' and 'phenomenotechnique' as an effective framework for a 're-thinking' of fluid simulation technology. By doing so, it aims to indicate a possibility for the expressive and imaginative usage and output of fluid simulation software through engaging with the philosopher's writing on science and technology and the elements of water, fire, and air. The chapter explains how Bachelard's notion of 'phenomenotechnique' blurs distinctions between scientific thinking and everyday experience and how scientific conceptions of the natural world reduce phenomena to our human connections with them. Following Bachelard's technical phenomenology, we can regard fluid simulations as instrument embodying knowledge of nature, and similarly, producing nature as a 'technophenomenon', an object designed for scientific study. With the notion of material imagination, the author bridges scientific thinking, technology, and everyday experience through practices of imagination which, I will argue to be an effective frame to think about- and make use of fluid simulation software. In conclusion, this thesis interprets a computational system through an analysis of its technical properties in combination with media theoretical discourses on the affordances of simulation versus representation, and the philosophical framework of elemental theory, to indicate the variety of methods and practices that can be used to study software as object that shapes and produces knowledge.

Chapter 1

Fluid simulation: a software archaeology through the ACM archive

Nonlinear simulation: mediating control

To better understand fluid simulation technology and its linkage to the US military-industrial-complex, it is valuable to discuss the writing on nonlinear system simulation by Jordan Gowanlock in *Animating Unpredictable Effects*. As fluid simulation is a nonlinear system and is also specifically addressed in the work by Gowanlock, this chapter first discusses the uses of nonlinear simulation and how it enabled a specific relationship with unpredictability. In *Animating Unpredictable Effects*, Gowanlock conceptualizes a relationship between the field of engineering and the visual effects industry through an analysis of the development of simulation technologies for animation. According to the author, studying nonlinear simulation specifically, offers insights into a paradigm of control that is shared between animation and computational visualization and many other fields that simulate nonlinear systems, like climate science, sociology, management science, and financial mathematics. By the means of programming unpredictability, this simulation technology has shaped many aspects of society since the 1940s.[25] The influence of nonlinear simulation on society is historically explained by the institutionalization of the field of "Research & Development". As part of the formation of the United States OSRD (Office of Scientific Research and Development) where engineering, technical training and scientific research were combined into one institution. Funded and regulated by the US government, simulation technology was a specifically important topic of research at "R&D" places like MIT and Caltech. Simulations were developed for purposes of propellor design, wind tunnels and other types of aeronautic research. By creating conditions that mimic those of the real-world, simulations as such provide insight into the dynamic properties of physical airstreams. Gowanlock primarily focusses on the institutional and industrial history that influences advances in R&D in relation to techniques for animation and visualization. Therewith, *Animating Unpredictable Effects* makes clear how these technologies produced a new form of knowledge born out of an industrial and governmental desire for technological advance situated in the United States. This way of knowledge creation is based on the development and design of a model based on a theory, which needs to be tested under certain conditions. Therewith, Gowanlock mentions how computer simulation is in essence a form of engineering epistemology. Simulation does not necessarily provide empirical knowledge, as coming from actual events, rather, it mimics these events to test and predict. As Gowanlock turns to nonlinear animation as tool for visualization, the author stresses the importance of remaining critical of the militaristic-, political- and cybernetic discourses that structure development in the field of R&D. However, importantly, this should not lead to a disregard of the theoretical complexity embedded in the way of thinking that is advanced by computer simulation.[26] Even though many disciplines use nonlinear simulation to control- and

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[25] Jordan Gowanlock *Animating Unpredictable Effects*, 2-3.

[26] Jordan Gowanlock *Animating Unpredictable Effects*, 34-36.

exploit the unpredictable, these simulations are also effective tools for purposes of speculation and imagination.[27] These insights offered by Gowanlock are useful for an analysis of fluid simulation as example of nonlinear system simulation. As the development of the technology is similarly structured by discourses of management and control over uncertainty, this development history seems valuable for the way that is shapes its possible usages and outputs. As previously mentioned, Gowanlock discusses the development and institutional history of fluid simulation technology. However, *Animating Unpredictable Effects* does not necessarily engage with the technical properties of simulation. As will be argued in this chapter, the technical specificities that structure this simulation software can make visible the theoretical complexities of the system, as well as a certain way of thinking about the object that is simulated, in this case natural phenomena like water, air and fire. Accordingly, to understand *how* this technology creates visualizations of our natural environment shaped by a paradigm of control, this chapter takes a closer look at the mathematical concepts and properties that structure fluid simulations. This will be done using Robert Bridson's *Fluid Simulation for Computer Graphics* (2016), for general concepts and structures, and "The Elements of Nature: Interactive and Realistic Techniques" (2004), the course manual found in the ACM SIGGRAPH archive. As will be argued, studying the technical structure of fluid simulation technology can offer important insights in what it enables and prevents to do.

Fluid simulation: the mathematics and the descriptive

As mentioned by Robert Bridson in *Fluid Simulation for Computer Graphics* (2016), fluids surround us everywhere, and are at the core of some of the most impressive phenomena we know. Therefore, splashing waters and whirling fires have become an important part of computer graphics research.[28] Similarly, the course introduction to "The Elements of Nature: Interactive and Realistic Techniques" in *ACM SIGGRAPH 2004 Course Notes* mentions how the photorealistic simulation of nature is one of the most challenging, ongoing problems in computer graphics. The course provides a follow-up on a SIGGRAPH '94 course on the same

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[27] Jordan Gowanlock *Animating Unpredictable Effects*, 18.

[28] Robert Bridson, *Fluid Simulation for Computer Graphics* (Boca Raton London, New York: CRC Press, 2016), 3.

subject, where this topic was discussed purely from an academic perspective. However, since then, great advances have taken place in modelling nature and a new era in computer graphics stimulated by the programmability of the graphics processing unit (GPU) and increased CPU performance, enables the simulation of natural phenomena at interactive, or near-interactive rates. Therefore, this course offers new insights into simulating complex natural environments by offering both the perspective of the academic research community, as well as that of the commercial production industry.[29] A combined reading of above-mentioned works offers a general overview of the mathematical properties and basic formulae used for fluid simulation algorithms together with case studies that describe adaptations of these algorithms to achieve very specific simulation goals, like the animation of complex deep-water surfaces, or achieving a "choppy look" for water animations.

To understand how specific ways of thinking about natural phenomena can be found embedded in fluid simulation, we first need to understand the basic equations on which the simulation algorithms are built. Understanding this enables an analysis of how certain mathematical properties in these algorithms are adapted and changed to achieve visual results. For example, in "Visual Simulation of Smoke", featured in the SIGGRAPH manual, Ronald Fedkiw explains how an adaptation of the numerical methods used in computational fluid dynamics are exploited to design a method that is unique to the visual characteristics of smoke as "appearing alive" by movements of rolling and curling.[30] A zooming-in on these types of descriptions of the specific visual needs per natural element, and their translation into mathematical logic provided by their combined origin in computational fluid dynamics, offers important insights into how natural phenomena are perceived and which characteristics are seen as most important to achieve realistic visualizations. Moreover, it makes apparent the type of visualizations that are possible through a language of mathematics and computational science. This last notion can be used to question what type of knowledge of these natural phenomena might be particularly hard to describe through computation and is therewith

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[29] Oliver Deusen et al., "Course Introduction," in *ACM SIGGRAPH 2004 Course Notes* (New York, NY: Association for Computing Machinery, 2004), 1-1, https://doi.org/10.1145/1103900.1103932.

[30] Ronald Fedkiw et al., "Visual Simulation of Smoke," in *ACM SIGGRAPH 2004 Course Notes*, ed. Oliver Deusen et al. (New York, NY: Association for Computing Machinery, 2004), 4-1.

perhaps lost in the process of visualization. As mentioned in "Practical Animation of Liquids" by Nick Foster and Ronald Fedkiw, animation is primarily about control. The difficulty with physics-based animations is providing the ultimate level of control, whilst maintaining the realistic behaviour of these types of phenomena. As liquids will always swirl and splash because of their governing equations, the level of control is necessarily limited.[31] Accordingly, fluid simulation offers an interesting insight in a tension between the unpredictable behaviour of natural phenomena and the use simulation as tool to direct and control this behaviour.

An overview of the basic fluid-equations

Generally, the fluid flows of water, air, smoke, or fire for animation are calculated by the incompressible Navier-Stokes equation. This is a partial differential equation which describes the motion of a fluid by calculating its speed, density, pressure, and its viscosity.[32] To describe fluid motion, these properties need to be calculated according to a predefined, geometrical space according to which change over time can be measured. Accordingly, the basic setup for visualizing fluid motion requires a predefined notion of space and input that allows for the numerical calculation between measured points. To track this motion, a specific viewpoint needs to be addressed. Here, there are two leading methods that are most frequently used, sometimes in combination with each other. The Eulerian- and Lagrangian viewpoints are common approaches to follow the movement of fluids through space. The difference between the two is based on the way they perceive the fluid as object. Where the Eulerian viewpoint calculates the fluid as entity passing through a fixed grid, the Lagrangian version deals with fluids as particle system, treating each point separately by its own position and velocity. Whereas the latter is faster to use and more intuitive, its accuracy is worse when particle-density is low. Therefore, this method is mostly useful when particles form a mesh, for example in solids. As the Eulerian viewpoint looks at fluid quantities according to fixed points in space to measure changes, it can track motion even when particle density is low. Bridson provides an example to clarify the difference between the two viewpoints by explaining that the Eulerian

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[31] Nick Foster and Ronald Fedkiw, "Practical Animation of Liquids," in *ACM SIGGRAPH 2004 Course Notes*, ed. Oliver Deusen et al. (New York, NY: Association for Computing Machinery, 2004), 4-34.

[32] Robert Bridson, *Fluid Simulation for Computer Graphics*, 3-4.

viewpoint calculates fluid motion as if standing on the ground whilst measuring the pressure and speed of air passing. The Lagrangian method, however, offers a viewpoint as if located in a balloon, measuring these properties whilst floating with the wind. Importantly, the Eulerian viewpoint works according to a fixed notion of space that will not change as the fluid passes through whilst the Lagrangian calculates motion according to a particle system that does not need to be connected by a mesh.[33] These characteristics of each viewpoint has an effect on the way in which a fluid can be calculated and according to which properties its visualization can be performed.

Another important aspect of the Navier-Stokes equation is its incompressibility. Fluids, be it gases or liquids, change volume. Disturbances in the volume of fluids similarly leads to changes in density and pressure. However, the volume changes that occur in fluids are usually very little. So little that our human sensory system is generally unable to register these changes. Since we cannot perceive these volume changes visibly, this characteristic is seen as irrelevant for animation. Therefore, the mathematical equations generally treat all fluids, be it smoke or water, as incompressible which means that their volume does not change and the same formulae can be applied to either type of fluid.[34] This notion is part of a seemingly important rule in simulation; the simpler the equations, the better. Following this rule means to only include those properties that are important for the visual outcome of the animation. Less important are those aspects that might be part of the physics that define natural phenomena in real-life, but do not play an important role in visual accuracy.[35] Another example of this, is that viscosity forces are often excluded from the basic fluid equations. In many cases, viscosity is of minor importance and is therefore not included. Not because water and air are lacking viscosity but as explained by Bridson, the contribution of this property to the numerical simulation is insignificant for its visual outcome and therefore not worth modelling.[36] The properties of pressure, speed, and density deal with the internal aspects of the fluids, but their behaviour is similarly influenced by what happens at the surface. To visualize fluid behaviour

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[33] Robert Bridson, *Fluid Simulation for Computer Graphics*, 7-8.

[34] Robert Bridson, *Fluid Simulation for Computer Graphics*, 11.

[35] Donald P. Greenberg, "A Framework For Realistic Image Synthesis," 44.

[36] Robert Bridson, *Fluid Simulation for Computer Graphics*, 13.

properly, boundary conditions need to be set to be able to calculate what happens to the fluids when for example encountering a solid object. Calculating how fluids move when passing a solid has much to do with velocity, as generally fluids do not continue moving into a solid object. This boundary condition requires setting the right properties for the interaction between the fluid and the type of solid it encounters to mimic the accurate visual behaviour. However, when a fluid interacts with a free surface, for example splashing waves, the boundary object is another fluid namely, air. Since simulating air alongside the already complicated task of simulating water requires highly complex computational efforts, air is simplified to be represented as an atmospheric region with constant pressure. Other than with a solid boundary condition, free surfaces do not need to control velocity as much and therefore requires less modelling of the fluid itself. Bridson provides another interesting example of a solution to free surface boundary conditions when discussing the simulation of smoke in open air. As it would be impossible to compute the entire atmosphere of the Earth, a selected grid is assigned to compute only the region that is expected to look "interesting". Accordingly, only the air close enough to the smoke is simulated and 'distant air' is excluded. Treating air as a constant region becomes difficult when simulating bubbles in water. Here, air needs to keep its volume and needs to be treated as an incompressible fluid, with the liquid itself as boundary condition. Treating the liquid as a free surface would make the bubbles collapse, as it disregards its volume and therefore this scenario requires a simulation of both air and water.[37] Seemingly, the complexity of interactions between natural phenomena require all kinds of tweaks and adjustments to achieve a visually convincing result. These tweaks seem to be based on 'simple' simulation illusions rather than accurate physics as the latter are too complex to compute.

Lastly, Bridson discusses how continuous equations need to be divided into individual counterparts for a numerical simulation to be suitable for computation. Two important aspects of the splitting of fluid equations are highlighted: time and space. Firstly, the chosen time-steps influence how fast things can move in the simulation and can limit motion per step in time. Over- or under-sampling can result in inaccurate visual results of the liquid motion. Another thing that heavily influences the visual outcome of the simulation algorithm is the grid.

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[37] Robert Bridson, *Fluid Simulation for Computer Graphics*, 13-16.

Generally, fluid simulations work according to a Cartesian grid which is composed of squares aligned with axes corresponding to the Cartesian coordinate system.[38] The Cartesian is the most common coordinate system used in computer graphics, usually representing a three-dimensional Euclidian space.[39] However, for specific fluids, solving them on a Cartesian grid is not always seen as the most favourable. Interestingly, when visualizing smoke, foam bubbles or mist; phenomena that weakly effect the flow of a fluid, a different representation is seen as more effective. These phenomena are introduced to the simulation by adding particle methods.[40] Important is the note here by Bridson to keep in mind the user of the algorithm. The author stresses the importance of keeping in mind that a user can only control those parameters that are "physical" and not the ones relating to time steps or the grid size.[41] Interestingly, the notions of time and space in the basic built-up of fluids simulation algorithms are to be defined prior and separately from its "physical" parameters like velocity, pressure, and density.

Thus far, there are some elements from Bridson's general overview of basic fluid equations that are important for this chapter. First, the incompressible Navier-Stokes equation that underlies fluid simulation equations is calculated by the general properties of speed, pressure, and viscosity. This seems to indicate that a visualization of elements like water, fire and air is primarily based on their changing movement between different steps in time, the amount of pressure exerted on something and the amount of deformation the fluids resist. These are properties that can be assigned a numerical value that only makes sense when these values are calculated according to a geometrical space. However, this space, as we have come to understand, is commonly based on a Cartesian coordinated grid. Therefore, in fluid simulation, water or fire can only be visualized through a language that measures these phenomena as objects which are capable of static measurements at a specific point in space and time. This space and its time-unit is predefined and therefore comes prior to the fluid.

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[38] Robert Bridson, *Fluid Simulation for Computer Graphics*, 21-27.

[39] Daniel Fontijne and Leo Dorst, "Modeling 3D Euclidean Geometry," *IEEE Computer Graphics and Applications* 23, no. 2 (March-April 2003): 69.

[40] Robert Bridson, *Fluid Simulation for Computer Graphics*, 107.

[41] Robert Bridson, *Fluid Simulation for Computer Graphics*, 114.

When for example thinking about water like a river flowing through a riverbed, it seems hard to assign a static point in time or space to measure the water. Rather, the phenomenon is in constant motion. An understanding of space as is forwarded in the structure of fluid simulation makes visible the object-oriented paradigm that structures its mathematics. Moreover, the commonly used Eulerian viewpoint works according to a predefined grid onto which an observer is looking at the phenomenon. Seemingly, simulations calculate and make sense of natural phenomena from a position located outside of the elements, and unaffected by them. In the chapter "Western Mathematics: The Secret Weapon of Cultural Imperialism" in *The Post-Colonial Studies Reader* (2003), Alan J. Bishop writes about this 'objectism' structuring Western mathematics. According to Bishop, the values associated with Western mathematics embed a way of seeing the world as if comprised of individual objects that can be abstracted and detached from their contexts. Moreover, Bishop specifically addresses how Western mathematics centres around a notion of generalization and instrumentalization through its ideas of space, time, length, volume, and weight which have been particularly applicable in the process of colonization, regarding trade, administration, and currency. For example, a different understanding of space and time that perceives everything as in constant motion seems difficult to represent through this normalized system of mathematics.[42] When considering a river again, it seems hard to understand it as separate from the environment it passes through. Moreover, for things and entities residing *in* the river, it is an environment on its own that could possibly make sense according to a different coordinate system than the Cartesian system underling Euclidean geometry that structures orientations according to ideas of points and lines. This example can make visible how notions of generalization and instrumentalization can be found embedded in the mathematical structure of fluid simulations. Something similar can be seen in the incompressibility of fluid equations as it disregards volume changes in liquids and gasses because these are imperceptible to us as humans. Not only does this indicate a generalized understanding of humans-standing-on Earth as the privileged way of

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[42] Alan J. Bishop, "Western Mathematics: The Secret Weapon of Cultural Imperialism," in *The Post-Colonial Studies Reader*, ed. Bill Ashcroft, Gareth Griffiths and Helen Tiffin (London and New York: Routledge, 2003), 72-75.

knowing the environment, it also standardizes natural elements by enabling the calculation of water, wind and fire through similar equations.

Understanding how notions of rationalization, instrumentalization and object-oriented perspectives dictate the mathematics that structure computational simulation and visualization can help further question what conceptions of natural phenomena might be made especially difficult. Even though generalization and standardization are at the core of these mathematics, visualizing water, fire, or air does need specific adjustments to these basic equations. In the following, a discussion of these adjustments per phenomenon can help to understand how each incorporates characteristics and challenges for which the basic equations need tinkering. This process can make visible what is needed to visualize each specific element through methods of simulation, and therewith, make understandable what is needed to perceive these simulated natural phenomena as truthful.

Water: ocean depth and shallow waves

According to Bridson, a new component needs to be added to use the basic equations for visualizing water. When simulating water as a fluid with a free surface boundary condition, the water needs to change shape when interacting with air. This change of shape needs to be tracked and captured through geometry. The interaction between the surface of a body of water and the air in simulation is referred to as the air-water interface.[43] Modelling this interface is an important aspect of simulating water. As simulating air alongside simulating water is a complex and computationally heavy task, methods dealing with the air-water interface offer workarounds by creating the accurate visual effects of water interacting with air instead of simulating both. This interaction is specific for water, since the visual characteristics of water reacting to air differ from those of fire and air. The interaction of water with the power exerted by air, can transform a smooth surface into a rippled or even agitated one. For example, waves can splash or break and foam or spray will evolve. This type of dynamic motion that takes place at the surface of water is important for realistic visual effects, but difficult to model realistically using traditional Computational Fluid Dynamics (CFD) methods. Therefore, in the

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[43] Robert Bridson, *Fluid Simulation for Computer Graphics*, 123.

case of water, this is an important research subject in the computer graphics community. A seminal method is explained by Jos Stam in "Stable Fluids" (1999), featured in the *ACM SIGGRAPH 2004 Course Notes*. In the introduction, Stam mentions the lineage of fluid simulation algorithms originating from the field of CFD into computer graphics science and how the main deviation is caused by the need for visually accurate shapes of fluids and the achievement of fluid-like behaviour in real-time. Accordingly, it is important for an animator to work with fluids intuitively which is specifically challenging for swirling and splashing motion. To achieve this, Stam proposes a method that uses both the Lagrangian- as well as the Eulerian viewpoint to adapt the basic algorithms explicitly for the purpose of working with swirling flows in real-time. In terms of physical accuracy, this method is far removed from the original CFD model, as the flow it creates dampens too quickly to be physically correct. However, according to Stam, this 'inaccuracy' in physical terms is specifically useful for the purpose of animation since a flow that does not dampen quickly would be 'too chaotic and difficult to control' by the animator.[44] Interestingly, Stam explains how the physics-based model is adapted to achieve a tool that can be interacted with by an animator to create realistic visualizations. This example shows how the computer graphics community creates realism by modifying and experimenting with the physical laws embedded in these algorithms. This possibility to stray away from physical accuracy allows computer graphics researchers to freely tweak methods that increase visual realism. Finding solutions for the changing shape of water when interacting with air is an area of fluid simulation research that specifically allows for this type of experimentation.

Another specific characteristic of water that is important for accurate visualization, is its changing behaviour and shape according to depth. A seminal study specifically dealing with the modelling of oceans is "Simulating Ocean Water" by Jerry Tessendorf. This study from the *ACM SIGGRAPH 2004 Course Notes* and referred to by Bridson in the chapter on "Ocean Modeling", provides a method for the simulation of a body of water by solely focussing on the structure and motion of the surface of water. Deviating from the CFD methods, where surface motion follows from a correct physical simulation, this method proposes a combination of

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[44] Jos Stam, "Stable Fluids," 4-1-4-2.

oceanographic phenomenology and 'computational flexibility' to achieve realistic wave motion.[45] As wind and ocean currents are not considered in this simulation, the accurate amplitude and behaviour expressed by waves is not calculated. This method proposes phenomenological models as solution for this problem. These models are garnered from perceptual analysis and give insights into general assumptions of the behaviour of waves according to a chosen wind direction. As mentioned by Tessendorf, these models can be used as a basis structure after which they offer lots of freedom to experiment.[46] However, Tessendorf's method primarily applies to relatively calm oceans, since it does not include how to deal with breaking waves. It is primarily interesting for its method of creating the illusion of depth below the water, whilst solely dealing with its surface. This method convincingly simulates realistic waves by adjust their relative size to their speed which results in the realistic effect of both large-scale waves as well as ripples. This visual effect is what communicates there is a noticeable depth in a body of water. Tessendorf thereby created a method for a visual simulation of ocean depth, by repurposing the physics underlying it.[47]

A final important characteristic for simulating water, is the visual difference between the surface of shallow waters and those of deep waters. Specific 'shallow water equations' are developed to realistically mimic the lack of depth that results in 'thin' waves that move slowly, instead of fast waves in deeper water. Vertical variations are therefore ignored in the equations for shallow waters and only the horizontal velocity is tracked. This equation has also been applied to the modelling of phenomena like avalanches and large-scale weather patterns as these are characterized by the movement of a thin structure on top of a larger solid structure (e.g. a snow layer on top of a mountain, or the atmosphere around the Earth).[48] This model offers a huge simplification of the models used for ocean waters. However, whilst similarly visualizing water, the shallow water equation is completely wrong for purposes of ocean modelling.[49]

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[45] Jerry Tessendorf, "Simulating Ocean Water," in *ACM SIGGRAPH 2004 Course Notes*, ed. Oliver Deusen et al. (New York, NY: Association for Computing Machinery, 2004), 2-2.

[46] Robert Bridson, *Fluid Simulation for Computer Graphics*, 199.

[47] Robert Bridson, *Fluid Simulation for Computer Graphics*, 192.

[48] Robert Bridson, *Fluid Simulation for Computer Graphics*, 175.

[49] Robert Bridson, *Fluid Simulation for Computer Graphics*, 185.

Fire: thin flames and visual fullness

Realistic visual effects of fire are specifically popular because of the dangerous nature of the phenomenon. In “Physically Based Modeling and Animation of Fire” by Duc Quang Nguyen, Ronald Fedkiw and Henrik Wann Jensen, the authors explain the challenges of creating realistic animations of fire. According to the authors, to occur realistic, fire needs a visual ‘fullness’ caused by turbulence of the flames that is generated by the expansion of the fuel forming hot gaseous products.[50] Accordingly, their method captures the three most distinct visual aspects of flames that create such a ‘fullness’; the blue core, the blackbody radiation characterised by the yellow-orange flames, and lastly, smoke. However, next to these core visual aspects the paper mentions another specificity about fire in relation to other phenomena, its behaviour as a participating medium. This behaviour can be described through properties as scattering, absorption and emission and creates highly complex shapes where fire emits light. This scattering of light is highly complex to control and therefore an important subject of research for visual animation.[51] In another research paper found in the SIGGRAPH archive, Nguyen and Fedkiw clearly describe the difference between simulating water versus fire; as visualizations of water are primarily defined by dealing with the air-water interface through a passive tracking of the contact discontinuities between water and air, fire effects are defined by an active combustion process that results in visually chaotic behaviour.[52] Therefore, according to the authors, the process of simulating fire is defined by it being an active phenomenon. Interestingly, both fire and water are characterised by a visual unpredictability caused by their intrinsic behaviours. However, both need specific adaptations of the basic Navier-Stokes fluid equations to control this type of behaviour in favour of animation. An important method proposed in the study by Nguyen et al., is to model fire as an infinitely thin flame front. This method is also described by Bridson in the chapter on fire where the author explains this method as a simplification by modelling the combustion region as a surface, instead of a

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[50] Duc Quang Nguyen, Ronald Fedkiw and Henrik Wann Jensen, “Physically Based Modeling and Animation of Fire,” in *ACM SIGGRAPH 2004 Course Notes*, ed. Oliver Deusen et al. (New York, NY: Association for Computing Machinery, 2004), 4-21.

[51] Duc Quang Nguyen et al., “Physically Based Modeling and Animation of Fire,” 4-26.

[52] Duc Quang Nguyen, Doug Enright and Ronald Fedkiw, “Simulation and animation of fire and other natural phenomena in the visual effects industry,” *Western States Section Combustion Institute* (Fall Meeting, UCLA, October 2003): 18-19.

volume. Accordingly, to achieve visually plausible results, this method describes fire according to a phenomenological approach and an assumption of premixed fuel and oxidizer before ignition.[53] Even though not physically correct, this model does offer a simplification for the highly complex physics of the combustion process of fire.

Air: turbulence and atmospheric rendering

The natural phenomenon of air is something inherently difficult to visualize as it only becomes apparent when interacting with other things. When air causes leaves to flutter, water to splash, or clouds to drift it makes itself noticeable as wind. Other than wind, air is always present in the atmosphere surrounding Earth, even when unnoticeable. Wind is the movement of air between high- and low-pressure areas and expresses itself in different speeds and directions. In relation to the other natural phenomena discussed in this chapter, air is a vital element. The continuous movement of water on-, above and below Earth cannot exist without air. Similarly, fire is depended on fuel, heat, and oxygen to ignite. However, as mentioned in the previous chapters, air is not included in simulations of water or fire. Rather, the interactions between water or fire and air are modelled in such a way that the visual result is plausible but bears no resemblance to the physics of a real-life environment. This makes air an interesting phenomenon regarding fluid simulation. Since the visual appearance and behaviour of water and fire are completely dependent on their interactions with air, it seems particularly difficult to model this behaviour without including air in the computation. As it would cost much computational power and additional complex algorithms to simulate air alongside simulating water or fire, the interactions are best faked in favour of real-time modelling and improved resolution. However, an aspect of air which is important to include in fluid simulation is turbulence as this causes the swirling and rotating movement that is important for realistic animations of both water and fire. As mentioned by Bridson, other than the close relationship between fluid simulation and its scientific counterpart in computational fluid dynamics, the methods for simulating turbulence have little ties to scientific examinations.[54] As turbulence is

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[53] Robert Bridson, *Fluid Simulation for Computer Graphics*, 133.

[54] Robert Bridson, *Fluid Simulation for Computer Graphics*, 163.

characterized by chaotic changes in pressure and velocity, it causes interactions that result in highly complex and unpredictable behaviour. Therefore, turbulence continues to be a huge scientific challenge.[55] Next to chaotic and unpredictable behaviour, turbulence creates movement on an enormous range, from incredibly wide in the atmosphere, to very detailed in for example, a small region of water. To simulate such a wide range and their causal relationship seems impossible. However, Bridson mentions this problem can be solved for purposes of animation. As the author describes, small-scale turbulence is isotropic, meaning that statistically, detailed regions of turbulence look visually alike any other region.[56] Therefore, it suffices to only zoom-in on small-scale turbulence and disregard its large-scale motion.

Moreover, to model the specific swirling motion that occurs with turbulence, a procedural velocity field is needed. Procedural techniques are algorithms that specify certain characteristics of a computational model, without the need for dealing with complex details. Through the abstraction of these details into a function or algorithm, this approach uses less storage and limits the time spend for the programmer to specify details to the computer. This method allows for parametric control enabling the possibility to assign concepts to numerical parameters. For example, increasing or decreasing a value can make a wave "rougher" or "smoother".[57] This form of automation provides a user with control over large-scale changes, whilst similarly limiting control over the small-scale specifications of details. Accordingly, using a phenomenological approach, procedural turbulence allows for visualizing the swirling motion generated by atmospheric pressures without the need for accurate physical laws. As concluded by Bridson, there is a fine line between automating the amount of turbulence in a simulation and the possibilities for artistic intervention.[58] This section on air and turbulence is important to consider as it shows how perhaps the most defining aspect of the behaviour of natural phenomena, their interaction with air, is not part of their simulation. Moreover, the realistic visual output is based solely on visual knowledge of how natural elements react to turbulence

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[55] I. Eames and J. B. Flor, "New developments in understanding interfacial processes in turbulent flows," *Philosophical Transactions of the Royal Society A* 369 (2011): 702, DOI:10.1098/rsta.2010.0332.

[56] Robert Bridson, *Fluid Simulation for Computer Graphics*, 163.

[57] David S. Ebert, "Interactive Cloud Modeling and Photorealistic Atmospheric Rendering," in *ACM SIGGRAPH 2004 Course Notes*, ed. Oliver Deusen et al. (New York, NY: Association for Computing Machinery, 2004), 6-2-6-3.

[58] Robert Bridson, *Fluid Simulation for Computer Graphics*, 172.

and automated through procedural modelling. This process turns specific details into implicit procedures through abstraction.

Simulating artistic control

Thus far, we have looked at how specific adjustments are made to basic fluid equations to create realistic visualizations of respectively, water, fire, and air. This chapter highlighted what are considered some of the most important visual characteristics of each phenomenon needed to achieve convincing results. The main purpose of these methods is to appear as true to life as possible. In the case of water, the interface between water and air needs to be modelled in such a way that it can visually express dynamic motion like rippling or splashing. Moreover, this type of dynamic motion needs to coincide with the type of water simulated. Shallow water and ocean water behave differently and need specific equations to deal with the visual behaviour caused by the amount of depth. Accordingly, we have discussed some of the principal methods dealing with these challenges. Integrating particle methods to the basic grid structure as proposed by Jos Stam allows for a deviation from accurate physics and offers opportunity to control the swirling motion of water. Additionally, the shallow water equation as described by Jerry Tessendorf, realistically mimics the movement of 'thin' waves with little depth. This method ignores any type of vertical variation and is therefore ineffective for ocean, modelling, but useful for modelling other phenomena like avalanches, or large-scale weather patterns. When discussing fire, an important characteristic that defines its visual credibility is its behaviour as a participating medium. Fire scatters, emits, and absorbs light which makes it an 'active' phenomenon. Visually, this results in turbulent flames that form highly complex and chaotic shapes. A seminal study by Nguyen and Fedkiw proposes a method that models fire as an infinite flame front whilst disregarding the volume of the combustion process. By focussing on surface-modelling only, this method offers a simplification for the highly complex physics of combustion. Accordingly, only the 'outer' aspects of fire, the ones we visually register, are animated without the need for simulating the correct physical process.

Interestingly, we have seen that the complex and unpredictable shapes that produce visually plausible simulations of water surfaces and flames are modelled through methods that alter or even neglect the physical laws that describe type of motion. This mainly becomes apparent when we look at the simulation of air. As air only becomes visually perceptible when interacting with other things, it is the ‘shape’ of these interactions that are important for visual simulation. Simulating interactions with air according to accurate physical laws would be incredibly complex. Therefore, the movement created by air for purposes of animation is faked to occur realistic. This is done by modelling visual turbulence. As explained by Bridson as well as by David S. Ebert in “Interactive Cloud Modeling and Photorealistic Atmospheric Rendering”, through a process of procedural modelling, the many details and complexities that create turbulence can be abstracted and simplified to generate automated turbulent motion. Through parameters carrying pre-defined concepts, an animator can partly control aspects of turbulence by means of increasing and decreasing certain values which affect things like “roughness”. This method of dealing with the motion that occurs when phenomena like water and fire interact with air, creates a process in-between computational automation and manual manipulation. Parameters can be shifted and changed by a user which will create different visual results. However, the concepts that are added to the numerical values are pre-determined and the result of a process of abstraction of detail. Therefore, there seems to be an interesting tension in using fluid simulation for animation as the technology facilitates a notion of control over phenomena that seem to be inherently uncontrollable. An artist, however, can use the technology to ‘direct’ the behaviour of these types of phenomena according to their own conceptions to create the desired visual result. The way in which uncontrollable and complex behaviour is mediated through simulation results in a process that can be conceptualized as residing between theory and experimentation.[59] Accordingly, a core aspect of simulations of water, fire, and air, namely the perceptual knowledge of their behaviour, is pre-defined and built-in in the technology, but can be adapted and changed by users according to their own understanding of these phenomena. Procedural processes as such are mentioned by David S. Ebert as to free the user of any constraints posed by complex physical laws.[60] Seemingly, through abstraction and procedural methods, simulation provides a sense of control

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[59] Jordan Gowanlock *Animating Unpredictable Effects*, 20.

[60] David S. Ebert, “Interactive Cloud Modeling and Photorealistic Atmospheric Rendering,” 6-3.

over real-world phenomena, whilst simultaneously offering the idea of creating as-if freed from any of the rules governing reality. Simulation, therefore, can be seen to occupy an interesting space between automation and expression. As mentioned by Gowanlock, even though the visual output of simulation is often understood as representation, the specific process of creating through simulation is argued to differentiate it from other technologies for representations like methods of recording or sensing. Instead of creating images *of* an existing reality, simulation operates *as* a reality by adapting and changing according to feedback from a user.[61] In the following chapter, this difference between simulation and representation is further discussed to understand how fluid animations makes meaning through simulation. This helps understand how fluid simulation mediates conceptions of reality different from media for representation which is argued to be important for the specific way of creation afforded by simulation.

Chapter 2

Fluid simulation and representation: elemental imagination

Simulation: mapping reality

As discussed in the previous chapter, fluid simulation software enables a practice of making that resides in-between procedural-, automated processes, and manual manipulation. Accordingly, an animator can adjust parameters to achieve the required visual results. However, the concepts assigned to the values of these parameters are pre-defined. For example, an animator can adjust the height of ocean waves to make it appear more agitated, but the option to adjust wave-height is already built-in in the software. Therefore, the options offered by the technology influence its usage, whilst simultaneously enabling a practice of creating that is experimental and creative. Moreover, the previous chapter introduced nonlinear simulation as a technology used for the prediction of unpredictable, complex systems and therewith, a technology that can be seen as mediating our human relationship with notions of risk, chaos, and control. The chapter discussed the mathematical concepts that structure basic fluid

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[61] Jordan Gowanlock *Animating Unpredictable Effects*, 44.

equations and their adaptation into effective fluid simulation algorithms that create realistic visualizations of water, fire, and air. The success of these simulations is defined by their ability to create visualizations of these natural phenomena that are as realistic as possible. As discussed, the main challenge is the visualization of the complex shapes that arise when water and fire interact with air. The unpredictable, and swirling motion that characterizes these interactions are visually simulated through methods of modelling turbulence. A recurring aspect in the described methods is that they achieve this type of complex behaviour by disregarding the aspects of the physics that define this same unpredictability in real-life environments. Therefore, it was argued that the technology of fluid simulation offers an interesting insight in the usage of nonlinear system simulation as tool for visualization. The basic structures of this technology are rooted in its military- and industrial usage where unpredictable phenomena need to be managed and optimized in favour of human-technological advancement. Therewith, nonlinear simulation creates uncertainty through computation to further control it. This chapter discusses how simulation for animation and visualization differs from other media for visual representation. Firstly, the chapter discusses how simulation specifically requires an understanding of *how* the technology represents as this is inherently different compared to media that represent through methods of recording of capturing. Secondly, the chapter addresses the usage of simulation for animation and how an industry-wide common goal of achieving hyperrealism has influenced the possibilities and limitations offered by these tools. Lastly, these notions are applied to fluid simulation to argue that the representational possibilities and limitations embedded in the technology are important to consider specifically when used to visualize our natural environment.

The differences between simulation and more traditional media for representation is explained by Gowanlock in *Animating Unpredictable Effects*. As argued in this work, where methods of recording or sensing create images and sounds of the world, simulation creates images by building a world from scratch. By recreating its material conditions, simulation operates as a world on its own, designed according to normalized conditions of understanding it.[62] Something similar is argued by Miguel Carvalhais in *Art and Computation* (2022).

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[62] Jordan Gowanlock *Animating Unpredictable Effects*, 178.

Through a discussion of the differences between simulation, imitation and emulation, the author identifies how computational media are inherently different from classical media for representation. Simulation is described by the author as creating a representation of a system in lower complexity to study its separate parts. Imitation, however, describes how a system can replicate another system and its actions, not by changing into the referenced system, but by mimicking its appearance. Lastly, emulation is described as the completely new instantiation of a system. Through means of transformation, emulation differs from the other two, as it not a simplification of another system, nor a replica, but a new system on its own. These differences are used by Carvalhais to explain that computational media augment classical media forms by developing something more complex than a recording or reproduction. Rather, computational media are not representations of something derived externally, but visualizations of data constructed by a representation of the medium itself. Following this notion, a computational simulation does not bear a relationship to an external reality by describing it but can be seen as operating as a reality of its own, unbound to specific materials or dimensions. However, by mimicking the output of classical media, we might understand and read this technology in a similar way. The author mentions how such an understanding of simulation can allow for a questioning of its mimetic tendencies by pointing out the clear difference between modelling something and representing it.[63] In *Simulacra and Simulations* (1981), Jean Baudrillard explains this difference comparably. Baudrillard describes simulation as generating models of a real without an origin and used the notion of the 'hyperreal' to further conceptualize a simulated reality. To clarify, the author uses the following example: where in simulation, the map precedes the territory, in representation, the territory always precedes the map. Therewith, simulations shape the real by creating its conditions before the act of representing, rather than representing existing properties.[64] Another difference between a simulation and representation, is the ability of a simulation to adapt. This is explained in the article "Towards a Reconceptualization of Simulation: From Representation to Reality" (1987). Written from a game theory perspective, the article points out how the "representational viewpoint" seems to

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[63] Miguel Carvalhais, *Art and Computation* (Rotterdam: V2_ Publishing, 2022), 41-43.

[64] Jean Baudrillard, "Simulacra and Simulations," in *Jean Baudrillard: Selected Writings*, ed. Mark Poster (Stanford: Stanford University Press, 2001), 166.

be the primary way of understanding simulation, causing the technology to be understood as objective and rational, as derived from scientific analysis. However, the authors argue in favour of the less-common view of simulations as "operating realities in their own right", without a direct representational capacity. As the authors explain, a combination of both viewpoints is needed to reconceptualize, and therewith better understand simulation technology.[65] The gaming perspective is especially useful here, since it considers how simulations are governed by a fixed set of rules that determine the system's behaviour and processes, affecting the possible usage of the simulation by users. Moreover, in the process of running, the simulation has the potential to adapt and change according to feedback of its environment. According to the authors, this makes a simulation perform as an operating reality, instead of a representation which would be incapable of such adaptation. The rules embedded in a simulation system enable its operation as a reality, whilst similarly offering guiding structures that define the possible usages. Additionally, the article mentions how what happens inside a simulation is defined by what users add to it from their own common-sense understandings of the real world.[66]

Accordingly, the rules that structure a simulation system, and which allow it to adapt to its environmental conditions whilst running, are an important argument for considering simulations as operating realities. Turning to fluid simulation specifically, the abovementioned difference between simulation and representation is relevant to address. Since the output of these simulations are visualizations which, when rendered, are no longer interactive, they are easily understood as representation. However, as the technology used to create these visualizations is simulation, what they represent are rather the specific rules and conditions that allow the simulation to run. Arguably, "knowing how" a simulation builds a reality becomes important in relation to "knowing that" it represents reality. This relates to the way in which Gowanlock uses work on philosophy of engineering by authors as Herbert Simon and Mario Bugne when discussing nonlinear simulation. To address the importance of

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[65] David Crookall, Rebecca Oxford and Danny Saunders, "Towards a Reconceptualization of Simulation: From Representation to Reality," *The Journal of SAGSET* 17, no. 4 (December 1987): 149.

[66] David Crookall, Rebecca Oxford and Danny Saunders, "Towards a Reconceptualization of Simulation: From Representation to Reality," 154-170.

understanding how knowledge is produced through computational simulation, Simon and Bugne argue for a revision of engineering as mere application of scientific knowledge.[67] In "Technology as Applied Science" (1966), Mario Bugne formulates a difference between the theories of 'pure-' and 'applied science' to argue that theories of applied science are often concerned with effects that occur- and can be controlled on a human scale. The applied researcher, therefore, is interested in finding out how to make things work for human-needs. Theories of pure science, however, are argued to be concerned with how things really are, independent from a human scale.[68] This line of thinking is used in the work by Gowanlock to address how focussing on a "knowing how" in addition to the "knowing that" allows for understanding the specific epistemic value of simulation technology. Where a focus on "knowing that" would offer a definition of simulation based on its qualities as representation; as it would with media technologies that record or capture, focussing on "knowing how" enables an analysis that considers the possibilities afforded by simulation technology as apparatus for building worlds.[69] In the case of fluid simulation, a "knowing that" would engage with the way in which the technology effectively resembles phenomena as water, fire and air. This relates to its outcome as representation and can be judged according to believability. A "knowing how", on the other hand, engages with the knowledge found in the rules and structures defined by computer scientists and artists to make the simulation perform accordingly. Therefore, it is argued that a "knowing that" in fluid simulation is primarily based on perceptual knowledge of the behaviour of the natural elements. This allows for an analysis of whether the result is realistic according to a human scale. However, a "knowing how", is based on questions regarding the performing of- and with the technology, the process of creating, rather than the outcome. This distinction is useful since addressing the "knowing how" of fluid simulation allows for a discussion of the rules that structure the technology and can therefore make visible what actions and output it enables, and those that it restricts. This is further elaborated upon in the last chapter, when discussing the work of Gaston Bachelard. The philosopher's notion of a 'technical phenomenology' is argued to be especially useful for

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[67] Jordan Gowanlock *Animating Unpredictable Effects*, 18.

[68] Mario Bugne, "Technology as Applied Science," *Technology and Culture* 7, no. 3 (Summer 1966): 332-333.

[69] Jordan Gowanlock *Animating Unpredictable Effects*, 44.

the consideration of a "knowing how" in relation technology and practices of sense making that are a joined process of scientific thinking, everyday experience and imagination.

Simulation in animation: hyperrealism

According to Gowanlock, the adaptation of simulation technology for animation purposes is more than a mere example of advancing digital tools. Rather, the author argues that these types of images can be seen as indicators of a continuation of the myths and cybernetic discourses found in the tools that precede them. An example of such a myth is the merging of our understanding of real phenomena with the computational simulations used to make sense of them. According to the author, such thinking can facilitate a discarding of differences between computational, emergent behaviour and the endless, unknown complexities of real life. The fact that animation uses adaptations of tools and concepts developed for scientific purposes indicates that these tools share a similar way of thinking about the world, as well as methods for understanding it.[70] This last notion is important in relation to fluid simulation as a technology that aims to achieve something Gowanlock refers to as 'hyperrealism'. In animation and digital media, hyperrealism is used by animation scholars to identify a type of imagery that intends to use well-known forms of representation, instead of using the possibilities of the representational freedom offered by animation as a medium. Instead of opting for hyper- or photorealism, animation scholars often praise a complete lack of representational fixedness that the medium is capable of. The medium's ability to morph shapes and a general notion of fluidity and formlessness, has been pointed-out to destabilize the representational fixedness of photographic cinema.[71] These morphing, abstract shapes enabled by animation have been described as residing in a state in-between process and transformation. Building on the seminal work of Sergei Eisenstein and the concept of 'plasmatic', media historian Norman Klein similarly theorizes these shapes through the concept of the 'animorph'. These plasmatic, and morphing shapes are seen as present and absent at the same time. For some moments, they do not represent what they are, or will be in the continuing sequence, and therewith create a sort

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[70] Jordan Gowanlock *Animating Unpredictable Effects*, 31-34.

[71] Jordan Gowanlock *Animating Unpredictable Effects*, 127.

of rupture that makes visible the medium itself, enabling the possibility to question what it represents.[72]

This conception of animation as having the potential to escape our settled ways of seeing and understanding the world is relevant in relation to the usage of simulation technology for visualization. As previously discussed, simulation differs from other media for representation as it operates as a reality on its own terms. Accordingly, like animation, simulation can destabilize our fixed ways of knowing. However, the aim of this technology for visualization is to be as realistic as possible. This aim affects the design of the technology itself. As mentioned in the article “Animated Expressions: Expressive Style in 3D Computer Graphic Narrative Animation” (2009) by Pat Power, around the 1960s naturalism and photorealism has become the primary goal of research in the field of computer graphics. Not in the least because of a pushing of this agenda by SIGGRAPH as the major cross-industry organization for computer graphics research.[73] Powers continues to explain that this resulted in the primacy of single-point perspective and photorealistic rendering in 3D animation to create the illusion of naturalism. This system of perspective is often understood as ‘subjective’ and ‘unique’, whilst simultaneously, it originates from the geometrical foundation for a mechanical way of “recording” reality.[74] These examples of the built-in mechanisms that favour hyperrealism, are specifically mentioned in relation to physical simulations used to visualize oceans, clouds, fire, and other gaseous effects.[75] Accordingly, the realistic agenda that structures simulation technology is particularly apparent for fluid simulation software. By drawing from cognitive science and neuro-aesthetics, Power mentions the effects that hyperrealism has on the stimulation of human memory, emotion, and imagination. Where realistic images evoke brain response alike mindreading and recognition, expressive imagery activates areas associated with emotional reward. This creates a different response with a viewer; where realistic images often seem to distract attention, expressive ones activate viewers into making aesthetic and

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[72] Vivian Sobchack, “The Line and the Animorph or ‘Travel Is More than Just A to B’,” *animation: an interdisciplinary journal* 3, no. 3 (November 2008): 261, DOI:10.1177/1746847708096728.

[73] Pat Power, “Animated Expressions: Expressive Style in 3D Computer Graphic Narrative Animation,” *animation: an interdisciplinary journal* 4, no. 2 (July 2009): 108-110, DOI:10.1177/1746847709104643.

[74] Pat Power, “Animated Expressions: Expressive Style in 3D Computer Graphic Narrative Animation,” 120.

[75] Pat Power, “Animated Expressions: Expressive Style in 3D Computer Graphic Narrative Animation,” 110.

imaginative connections.[76] With the article, Power aims to address and explore the expressive potential of 3D computer graphics and animation despite its hyperrealist agenda. In the following, abovementioned relationship between realistic and expressive imagery and their effects on imaginative connections is further explored in relation to the usage of fluid simulation for cinema specifically. As will be argued, even though fluid simulation technology is especially developed according to a realism-agenda, it would particularly benefit from the emotional and imaginative connections enabled by an expressive approach. Expressive usage of this type of 3D animation in relation to the natural elements is even argued to facilitate a questioning of persistent notions of the natural environment as-if captured by- and belonging to humans.

Fluid simulation and elemental imagination

In the previous chapter, the seemingly most important visual characteristics of water, fire, and air were discussed through the study of the *ACM SIGGRAPH 2004 Course Notes*. These course notes have shown that fluid simulation aims to achieve hyperrealism for which it needs to tweak many of the physical laws on which the technology was built. Accordingly, fluid simulation operates as its own reality far from the real-world environments that it represents. In this chapter, expressive versus realistic imagery was discussed in relation to animation technology. Fluid simulation is designed to achieve hyperrealism, however, as previously mentioned, the technology itself does not necessarily follow reality in the sense of accurate physics. Therefore, instead of thinking about these simulations as realistic, we could understand them as inherently fictional. Gowanlock argues something similar by mentioning that we should understand nonlinear animation as “fictionalized version of scientific simulation”. This notion is used to deconstruct the supposed objectivity of the realism created by simulation, not in the least caused by its relationship with the domains of science.[77] Moreover, this hyperreal form of representation has been identified by media scholars as restrictive and un-reflexive. This line of thinking understands nonlinear animation and

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[76] Pat Power, “Animated Expressions: Expressive Style in 3D Computer Graphic Narrative Animation,” 115.

[77] Jordan Gowanlock *Animating Unpredictable Effects*, 31.

simulated physics as to create representational forms that are borrowed from science and the military with its close-tied relationship between knowledge and power.[78] In *The Language of New Media* (2001), Lev Manovich writes about the instrumentalized and fixed realism embedded in (physical) simulation and the restrictive nature of their representational forms. The author discusses how realism in computer graphics should be understood as 'uneven' by comparing it with realism created through recording technologies for film. Where the (film) camera can point in any possible direction and record a reality that is already there, computer generated imagery can only capture the reality that has previously been constructed from scratch. Having computer simulation operate as a traditional camera, with the ability to record any aspect of the existing world, would be impossible because of the enormous mathematical complexity of all underlying physics. Therefore, computer graphics researchers have defined specific 'problems' that need to be solved to simulate the aspects of reality that are most 'useful'. Often occurring shapes, materials, movements, lighting, and effects are standardized to be applied to a variety of simulation scenes. In this process, choices have been made about aspects of reality that need to be made visible through computation, and which are of lesser importance. Manovich mentions how software libraries with standardized objects and effects are part of what differentiates the creation through computational applications from traditional media. In these applications, the process of making is influenced by the 3D models, textures, and behaviours that are already provided in by the software package.[79] According to Manovich, the curation of these libraries has less to do with our actual experiences of reality, and more with the reality traditionally recorded by the medium of film. Therefore, other than embodied experiences of the world, it is merely the film-based image that computer graphics is concerned with for simulation.[80]

This understanding is specifically useful regarding fluid simulation as it exemplifies that simulations are structured by subjects seen as valuable by the computer graphics to simulate realistically. As seen in the *ACM SIGGRAPH 2004 Course Notes*, natural phenomena like water, air and fire are such cases. The included research papers propose methods and

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[78] Jordan Gowanlock *Animating Unpredictable Effects*, 174.

[79] Lev Manovich, *The Language of New Media* (Cambridge, Massachusetts: MIT Press, 2001), 120.

[80] Lev Manovich, *The Language of New Media*, 174-181.

adjustments with a common goal of achieving ultimate realism when visualizing moving clouds, fire or splashing water. Manovich similarly mentions that “moving nature” has been a primary subject in computer animation, used to prove its authenticity. Film similarly demonstrated this value in comparison to the medium of photography by capturing natural movement, like the wind. Similarly, computer graphics has focussed on such subjects to validate its capabilities for realism. However, the inability of simulation to render reality as complete, has made researchers to fixate on achieving the ultimate realism for these specific types of subjects. Therefore, as Manovich argues, a computer-generated reality is inherently ‘uneven’ and incomplete. This argument is particularly useful since it facilitates a questioning of which things are visualized realistically, and what remains unseen in a simulated world. Moreover, following Manovich, the visuals created through simulation software are additionally biased since building a reality from scratch requires much know-how of the technology. Therefore, the pre-assembled, and standardized objects it contains become even more inviting for its users. Accordingly, the programs seem to dictate what type of visuals are easy to create and therefore become more prominent. Considering this, Manovich argues that ‘realism’ needs to be studied anew in the case of computer-generated imagery. Since these images are understood similarly to those created by photography and film, we have come to understand simulations as successfully faking reality. However, as the author demonstrated, the incompleteness and biases that structure simulated realism differentiates the technology from the media it tries to mimic.[81]

Accordingly, we can use this notion of incompleteness to question how this applies to the simulation of natural phenomena. As one of the main subjects for achieving hyperrealism, fluid simulation research has resulted in the development of many commercial applications which offer pre-set scenes and models. The visual effects and imagery generated using these applications are omnipresent in contemporary cinema as simulating phenomena as whirling fires or rough oceans is often both less expensive, as well as less dangerous or complex than filming live.[82] As we have come to understand, fluid simulation technology is structured by the goal of hyperrealism. Accordingly, this goal directs its usage. Many of the scenes featuring

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[81] Lev Manovich, *The Language of New Media*, 177-179.

[82] Robert Bridson and Christopher Batty, “Computational Physics in Film,” *SCIENCE* 330, no. 6012 (December 2010): 1756, DOI:10.1126/science.1198769.

artificial nature are based on the ‘film-image' we have of these phenomena. As previously discussed, Pat Power explicitly mentions how the design of animation technologies plays an important part in the output created with them. As hyper-realistic imagery is the privileged form of output of many applications, its interface and pre-defined effects are steered toward such usage. Therefore, these applications can make more expressive practices that include things like distortion or abstraction more difficult or counterintuitive.[83] In relation to visualizing natural phenomena such expressive usage of animation is specifically addressed by philosopher and film theorist, Ludo de Roo in “Elemental Imagination and Film Experience: Climate Change and the Cinematic Ethics of Immersive Filmworlds” (2019). De Roo mentions how 3D effects can unexpectedly connect us with the elements through otherworldly conceptions of liquidity, floating and other types of speculative use of natural phenomena. The author argues that a notion of “elemental imagination” can help us question persistent binary oppositions between humans and the natural world. Expressive and speculative visualizations of the natural elements in film, can facilitate an understanding of these phenomena not as something belonging to humans. Rather, engaging with landscape and nature through images that spark imagination, can help realize how we are always already placed within the elements ourselves. Such an elemental imagination is argued to allow for an experiential sense of ethics that is very different from ascribing normative morals and behaviours to the material world. Rather, it can reveal how human existence belongs to a sense of the world.[84] What this elemental imagination exactly entails is not entirely made clear by the author. However, De Roo argues that a cinematic imagination of the natural elements does not only reach the spectator on an affective level but can also nurture the opportunity of reorienting our senses in everyday experiences of the world around. Therefore, these imaginative conceptions play an important part in immersing us in the cinematic experience.[85] Accordingly, by “elemental imagination” the author ascribes potential to visualizations of natural phenomena in cinema to provoke action or change outside of their cinematic experience alone. De Roo specifically engages with

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[83] Pat Power, “Animated Expressions: Expressive Style in 3D Computer Graphic Narrative Animation,” 119.

[84] Ludo De Roo, “Elemental Imagination and Film Experience: Climate Change and the Cinematic Ethics of Immersive Filmworlds,” *Projections* 13, no. 2 (Summer 2019): 69-71, DOI:10:3167/proj.2019.130204.

[85] Ludo De Roo, “Elemental Imagination and Film Experience,” 59-60.

‘ecocinema’ by providing examples of documentary- and fiction films addressing climate change. The author mentions how blockbuster films offer “speculative imagination” by portraying exaggerated and dramatized visualizations of untameable oceans, or storms using computer generated imagery. However, the author continues saying that more and more, contemporary (eco)cinema scholars are paying attention to the use of nature as a thematically rich background outside of films with an explicit environmentalist theme.[86] De Roo argues that there is something specific to the medium of film that creates an experiential world for the spectator that is very similar to the real world. Therewith, even when depicting a technologically constructed version of nature, the cinematic experience can affect our experiences of natural phenomena outside of the screen.[87] Even more, De Roo turns to philosophers Gaston Bachelard and John Sallis to argue that this practice of imagination is most effectively guided by an expressive use of the natural elements. De Roo uses Bachelard’s notion of “material imagination” in literary representations of water, air, and fire, to argue for the inclusion of such an imagination in film. In Bachelard’s work, the literary “material image” of the elements becomes a phenomenological invitation for the reader to engage with dynamic, and imaginative conceptions of the world. Bachelard’s theory of imagination will be further explained in the last chapter of this thesis, where it will be proven useful for a discussion of the imaginative qualities of fluid simulation software. Additionally, De Roo uses the work by Sallis for the philosopher’s notion of a specific “elemental imagination”, broadening it, by taking it outside of mere literary expressions and bringing it to the force of the elements themselves. Sallis argues that it is from the elements that imagination arises, and which bounds us to the natural world.[88] Something similar is argued by Patrick D. Murphy in “Putting the Earth into Global Media Studies” (2011). The environmental communications scholar argues that the media form a central resource for conceptualizations of the natural world and serve as a means through which we can respond to environmental pressures of the earth. According to Murphy, the task for media scholars is to recognize and understand how the stories told and

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[86] Ludo De Roo, “Elemental Imagination and Film Experience,” 63.

[87] Ludo De Roo, “Elemental Imagination and Film Experience,” 65.

[88] Ludo De Roo, “Elemental Imagination and Film Experience,” 69.

imagery used, condition how people interpret and understand the environment.[89] Seemingly, Murphy describes a similar distinction here between a "knowing that" and a "knowing how", where the author emphasizes the importance of understanding *how* strategies of storytelling and visualizing influence our understanding of the world. In favor of this task, Murphy questions whether it is the role of media to foster a relationship with the natural world that is profoundly fantastical and imaginative. Following contemporary social-cultural anthropologist, Arjun Appadurai, Murphy adresses that mediated imagination can offer a disconnection with the cultural construct of the environment as a place "out there" that can be enjoyed as a consumer product, instead of a living force existing of interconnected ecosystems that we are a part of.[90] Accordingly, following abovementioned scholars, an understanding of the natural environment as living force is best communicated through practices of imagination. These scholars examine the human relationship with natural environments as represented through cinematic narratives.

In conclusion, the way in which we feature natural phenomena on screen influences our everyday experience of the real-world which seems to specifically benefit from imaginative conceptions of the elements. Fluid simulation, therefore, engages us through a notion of elemental imagination by depicting natural phenomena through media. However, the way in which these images allow for imaginative connections seems important as well. Even though De Roo specifically mentions 3D animation and its potentiality for an effective elemental imagination, the author does not engage specifically with the role played by technology in facilitating this type of imagery. Animation scholars like Power, however, explicitly mention how animation needs expressive usage to establish such imaginative connections as de design of the 3D technology is geared towards realism. Power even goes as far as to say that there is a certain danger in the use of computerization for visualization, as the work of a designer is at risk of being dictated by the language of the tools they use. This can be observed when certain tools or specific effects become fashionable and are so often used that they become ubiquitous

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[89] Patrick D. Murphy, "Putting the Earth into global media studies," *Communication Theory* 21, no. 3 (August 2011): 217-221, https://doi.org/10.1111/j.1468-2885.2011.01384.x.

[90] Patrick D. Murphy, "Putting the Earth into global media studies," 217-230.

or cliché.[91] With the goal of achieving hyperrealism, fluid simulation can be argued to make expressive or abstract usage counter intuitive. As a technology used to mimic the behaviour of real-world phenomena, expressive and imaginative usage of fluid simulations can possibly facilitate the construction of alternate, speculative worlds that question our settled ways of thinking about the natural environment. The following chapter engages with such speculative and alternate thinking about the natural elements through elemental theory. As argued by John Durham Peters in *The Marvelous Clouds: Towards a Philosophy of Elemental Media* (2015), a philosophy of media needs a philosophy of nature.[92] Elemental theory offers an undersranding of each natural element as having its own properties as a medium, and its own associative qualities. Therefore, each element involves different ways of perceiving and knowing.[93] Understanding why such elemental theory advocates for a thinking *through* the elements of water, air, fire, and earth, can help question what type of imaginative conceptions could possibly be applied to the usage of fluid simulation that counter its tendencies for realism. Moreover, specific conceptions of water, fire and air as forwarded by elemental theory are compared with the conceptions of these elements as they are characterised through simulation. Such a comparison can make visible what type of properties and knowledges of these natural phenomena are favoured in their computational translations and which might be missing.

Chapter 3

Elemental thinking: visualizing water, air, and fire

Elemental theory

The previous chapter discussed the tendency of physical simulation technology, like fluid simulation, to create output geared towards (hyper)realism. As discussed through the work of media scholar Lev Manovich, a computer-generated reality is inherently incomplete, as choices

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[91] Pat Power, “Animated Expressions: Expressive Style in 3D Computer Graphic Narrative Animation,” 124.

[92] John Durham Peters, *The Marvelous Clouds: Towards a Philosophy of Elemental Media* (Chicago and London: University of Chicago Press, 2015), 1.

[93] Patricia Pisters, “Combustive Knowledge: Fire as Medium and Interface,” *communication +1* 9, no. 1 (October 2022), 1, DOI:10.7275/xcye-wr43.

have been made by designers and developers as to which aspects of reality are particularly valuable to simulate. Accordingly, the objects, materials, effects, and movements seen as most important or effective receive the most attention in terms of research, and development. These objects are often part of a library of pre-sets in software applications, facilitating easy use. The work by Manovich was used to make clear how this bias in physical simulation technology resulted in hyperrealism as preferred form of visualization. Even though this form of realism reminds of that created through film and photography, it is this incompleteness of a simulated reality that differentiates it from a recorded one.[94] Different from film, a simulation does not point a camera and record an already existing reality, rather, it needs to build this reality from scratch.[95] According to Manovich, even though closely resembling reality, simulated scenes have less to do with our actual experiences of the world, and more with the world as traditionally recorded through film. Therefore, these simulations are based on a film-image of the world, instead of representing embodied experiences.[96] This seems to be specifically the case for fluid simulation. As "moving nature" has been a primary subject for realistic simulation to validate the technology's abilities of mimicking reality, simulations of phenomena as water, fire and air are steered towards hyperrealism. However, as argued by Pat Power, realistic imagery is less effective for establishing imaginative connections with a viewer in comparison with expressive and/or abstract imagery. De Roo makes a similar argument by calling for the usage of expressive and imaginative imagery specifically in relation to the cinematic representations of the natural elements. Through a notion of 'elemental imagination' the author argues that otherworldly conceptualizations and speculative use of natural phenomena can help question persistent binaries between humans and nature. By drawing from philosophers like Gaston Bachelard and John Sallis, De Roo argues that such an elemental imagination can question normative behaviours ascribed to the world by humans and reveal how human existence is embedded within the elements.[97] Accordingly, the imaginative and expressive usage of fluid

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[94] Lev Manovich, *The Language of New Media*, 177-179.

[95] Lev Manovich, *The Language of New Media*, 120.

[96] Lev Manovich, *The Language of New Media*, 174-181.

[97] Ludo De Roo, "Elemental Imagination and Film Experience: Climate Change and the Cinematic Ethics of Immersive Filmworlds," 69-71.

simulation can possibly stimulate such 'elemental imagination'. To understand what such imaginative conceptions of the elements entail, it is valuable to further engage with philosophy on the elements and nature. This chapter engages with continental philosophy and elemental theory to make insightful the relationship between the way we think about- and represent the natural environment and the elements of water, fire and air. The work, *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire* (2015), edited by J. J Cohen and L. Duckert, is a valuable source in this regard. As explained in its introduction, *Elemental Ecocriticism* builds upon philosophers like Bachelard and David Macauley, who have written about the elements through notions of environmental awareness, narrative, and art. The work aims to engage with literature from the past as means to discover an archive for thinking the environment anew. Through imaginative and critical thinking, these essays write against a reduction of the world into mere resource.[98] As further explained, the work aims to show water, fire, air, and earth as dynamic entities that, through persistent objectification, have been normalized as resources for controllable commodity. Accordingly, elemental ecocriticism turns to an understanding of the material vibrancy of the elements which is argued to have been obfuscated by mechanistic models. This vibrancy is found in the many histories that offer imaginings of nature as an active force and a material archive. As concluded in the introduction, thinking through the elements means thinking through the impossible, the imaginary and the unreal by exceeding a humanly knowable scale.[99] Moreover, elemental theory considers the natural elements as media in and of themselves through their individual affordances as well as the cultural imaginations associated with each element.[100]

This chapter discusses impossibilities and unknowns of water, fire and air as theorized in a variety of essays featured in *Elemental Ecocriticism*, alongside the additional works; *Wild Blue Media: Thinking Through Seawater* (2020) by Melody Jue, *Elemental Philosophy: Earth, Air, Fire, and Water as Environmental Ideas* (2010) by David Macauley and the article, "Air as Medium" (2018) by Eva Horn. These insights are compared with the conceptualizations of these elements through simulation as discussed in the first chapter. This comparison can make

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[98] J. J. Cohen and L. Duckert, ed., *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire*, 3-4.

[99] J. J. Cohen and L. Duckert, ed., *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire*, 7.

[100] Patricia Pisters, "Combustive Knowledge: Fire as Medium and Interface," 1.

visible what knowledge on these elements might be lost when translated into computational object for realistic simulation, and which properties of simulation might be especially useful for purposes of imaginative conception. A comparison as such will show how both elemental theory as well as fluid simulation, are ways of imagining the elements based on impossibilities and/or the unreal, however, serving very different outcomes. Where the speculative thinking in elemental theory aims at destabilizing normative conceptions of the elements as resource, serving a human-centred perspective, the translation of the elements into simulation is argued to enforce, instead of question such thinking. Elemental ecocriticism supports a thinking that denounces the scaling, measuring, and pacing of the world according to a human point of view and therefore will be argued to contradict the way in which we think the elements through methods of simulation. As these simulations operate as realities on their own, it is argued that such a questioning can help the usage of this technology to think through objects, phenomena, and materiality according to a scale that exceeds the merely human.

A thinking through water

In “The Sea Above”, featured in *Elemental Ecocriticism*, Jeffrey Jerome Cohen explores a thinking through the notion of ‘sky becoming sea’, to confront us with our terrestrial-, land-bound perspective and exchanging it for the spiralling environments of water and air. According to Cohen, water and air are elemental intimates and their indefinite borders have been a place for cosmic dreaming. Sayings like “head in the clouds” and “at sea” are examples used by Cohen to clarify how we refer to this changing perspective as being in a state of drift or confusion offering both a cognitive as well as an affective disorientation from the supposed stable foundation of the earth. When thinking through the joining space of water and air as environments, the solids of the earth can become immaterial and transitory.[101] Cohen conceptualizes the meeting of water and air as a specific place for elemental thinking. Such a practice demands an ability to move beyond existing categories of knowledge and a welcoming of the unknown. Specifically, as described by Cohen, such thinking with the elements needs an understanding of the material world as exceeding us, humans. To realize our embeddedness

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[101] J. J. Cohen and L. Duckert, ed., *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire*, 112-113.

within a world of winds, seas, sky, and stones is to understand an environmental agency.[102] The author recognizes that thinking through beings and forces that exceed us is a difficult task. However, rather than simplifying, Cohen argues in favour of dealing with this complexity. Cohen uses the example of medieval historians and theologians that searched for a divine viewpoint that would offer a sense of control over the chaos of the earth, to show how such simplification is harmful as nature does not conform to the methods used to arrange, scale, and manage it. Accordingly, the author uses the thinking through the conjoining of water and air as method to understand that life is strange and complex and that such an understanding can help destabilize our terrestrial boundedness.[103] Imagining the sea above, instead of a sea to look down upon while standing on earth, is an example of engaging with the impossible and the imaginative in relation to our conceptions of the natural environment as practiced in elemental theory. Interestingly, Cohen uses the coming together of water and air as a place specifically useful for making visible our terrestrial biases. According to Cohen, the interactions of water and air offer swirling, entangled environments that defy notions of simplification and order according to a fixed point-of-view. Another scholar that uses notions of estrangement to think about water, and specifically, air water contact zones, is ocean humanities scholar Melody Jue. In *Wild Blue Media: Thinking Through Seawater*, Jue explores the ocean as an environment that destabilizes human-centred and terrestrial experiences of time, space, embodiment, and aesthetics. Thinking about submersion, pressure, and buoyancy in relation to the ocean can estrange us from- or make visible terrestrial habits of perception and movement.[104] Jue builds on Villém Flusser's story of the *Vampyroteuthis Infernalis*, the vampire squid, in which Flusser bridged science, philosophy and fiction to dive into the ocean through the phenomenological world of the vampire squid. Flusser's 'media fable', as Jue describes it, questions the anthropocentrism of media theory by questioning for whom and under which environmental conditions media exist. By bridging media theory with ocean diving and fabulation, Jue shows how thinking through the nonhuman environment of seawater requires a focus on the

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[102] J. J. Cohen and L. Duckert, ed., *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire*, 123.

[103] J. J. Cohen and L. Duckert, ed., *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire*, 124-127.

[104] Ann Elias, "Wild Blue Media: Thinking Through Seawater by Melody Jue," *Journal of Cinema and Media Studies* 61, no. 1, (Fall 2022): 201-202, https://doi.org/10.1353/cj.2022.0076.

materiality of the environment, as well as the user that is accustomed to its materiality as condition for thought.[105] Alongside the vampire squid, Jue touches on the nonhuman example of the “spherical being living outside any gravitational field” to make visible the anthropocentric ways of knowing the world that structure our vocabulary. In a way similar to the vampire squid, the spherical being offers a thinking through embodiment that differs from our human position as standing on earth. Therewith, Jue shows how orientational language and metaphorical uses of “up” and “down”, do no longer make as much sense when considering a spherical being. Most importantly, these thought practices allow Jue to argue that we are accustomed to interpreting the world positioned at its surface. This ‘surface dwelling’ has implications for our sense of spatiality and the ways in which we use orientational language.[106] Similar to Cohen’s conceptualization of the sky becoming sea, Jue’s thinking through seawater affords an estrangement of our human understanding of space and the position of standing on land as the normative condition for knowing and observing. Both authors think though water as an environment to address the subjectivity of human perspectives as they emerge from embodiment and lived environments. Accordingly, for both these authors a practice of imaginative thinking with the element of water allowed for a reconsidering of our human-centred conditions for knowing the world.

These examples of elemental thinking through water require imaginative conceptions that speculate on- or estrange us from our lived environments and the ways in which we are accustomed to them. Seemingly, both Cohen’s sky becoming sea, as well as Jue’s vampire squid and spherical being ask for a disposing of our normalized physical laws of nature. Cohen’s example placed us at the interface between air and water which exchanged all that is solid from the earth into a transitory and swirling environment that promotes complexity by resisting order through a single-point perspective. Moreover, the vampire squid living in the deep sea shows how the coordinate systems that structures our language and thinking about the environment, are not universal nor objective. Similarly, Jue’s spherical being ask for a different understanding of the world by discarding our rules of physics. These thought practices seem

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[105] Melody Jue, *Wild Blue Media: Thinking Through Seawater* (Durham, NC: Duke University Press, 2020), 74.

[106] Melody Jue, *Wild Blue Media: Thinking Through Seawater*, 83-83.

particularly applicable to fluid simulation. As argued in the previous chapter, the design of fluid simulation technology steers it towards realism. However, this technology achieves realism by speculating on physical laws. Accordingly, even though its realism supports an understanding as objective, we can think of fluid simulation as inherently fictional. Since simulations do not record an existing reality, but rather operate as realities on their own, the technology seems particularly useful for such elemental imagination. As argued by Murphy and De Roo, visualizing the natural elements through imaginative and expressive means was argued to create opportunity for a resetting of our senses in everyday experience of the environment. More specifically, Murphy argued that such conceptions of the elements can facilitate an understanding of the environment as something we are embedded in, instead of a place "out there" to be picked and used. With the potential to create affective experiences that transcend the screen and the ability of the technology to create alternate realities, fluid simulation can stimulate elemental imagination. However, I argue that such elemental imagination requires an understanding of the terrestrial biases that structure the technology, and therewith influence its usage. By drawing from Jue's thinking through seawater to analyse the technology of fluid simulation for visualizing water, the notion of 'surface dwelling', becomes specifically apparent. As mentioned in the first chapter, the seminal method proposed by Tessendorf to simulate ocean water was developed according to phenomenological studies on the behaviour of ocean waves. This method models ocean movement primarily according to observations of the surfaces of water, independent from current and/or wind directions. Moreover, the chapter explained how shallow waters are visualized according to different equations than deeper waters. In favour of simplification, shallow waters are calculated by ignoring vertical variation and only tracking the horizontal velocity. Such a variation of the general deeper water equations is in favour of a simplification of the simulation and is based merely on a phenomenological analysis of the surface of shallow water. Consequently, simulating ocean- and shallow water is inherently structured by our viewpoint as positioned at the world's surface.

Cohen's sky becoming sea similarly makes visible how fluid simulation is terrestrial-biased. As simulating air alongside water is computationally too complex, the interface between water and air is specifically in need of simplification. In this regard, the study by Jos Stam was mentioned. Stam's method proposes to combine a Lagrangian- and Eulerian viewpoint to adapt the equations explicitly for the purpose of swirling movement. In terms of physical accuracy, this method is far removed from reality. However, this inaccuracy is seen as specifically useful for the purpose of animation since the swirling motion would become too chaotic and difficult to control. Accordingly, this example shows how the contact zone between water and air is simplified to control and manage its complexity. The chaos and unpredictability that seems to be celebrated in elemental theory, is staged in these simulations according to phenomenological information on surface behaviour. Fluid simulation, therefore, offers control over the illusion of complexity at the air-water-interface without dealing with the actual complexities that define this movement in real life. The phenomenological approach of fluid simulation, based on a human-centred viewpoint is contested in elemental theory by situating us in the swirling environment of water and air to make visible how, in such an environment, our normalized understanding of orientation and movement are not applicable.

A thinking through fire

In the work *Elemental Philosophy: Earth, Air, Fire, and Water as Environmental Ideas* (2010), philosopher David Macauley describes fire as a meta-organic technology that requires control, care, and cultivation, rather than domination or elimination. Macauley mentions three different phases of fire to argue how nature's "First Fire", that ignited millions of years ago, developed into an anthropogenic, "Second Fire". This second phase is one where the human control of combustible fuel has shaped and reshaped the natural environment. This phase has paved the way for our current period of "Third Fire", where through industrial processes, fire burns in confined spaces, rendering the open flame increasingly unseen. According to Macauley, unlike water or air, fire seems specifically connected to magic as it has the capacity to ignite, or to be summoned through hardly any craft, after which it influences and shapes the natural world and mesmerizes the human mind. However, the open burning of fire, which allows for such mesmerizing and worshiping, has been replaced by fire as hidden combustion. Therefore, fire has become something we do not truly perceive anymore. Rather, we know fire as something contained, something we can ignite, but rarely encounter in unmediated shape.[107] Macauley calls this 'anthropogenic fire' and uses this notion to question what it means for our understanding of the element. Following Macauley, our domestication of fire seems to have simplified its multiple stages of incipient, emergence, smouldering, ignition, and initial combustion, into the visible flame. In "Pyromena", Anne Harris builds on the work of Macauley and describes fire as a living thing without a clear beginning or end. Harris emphasizes the ability of fire to create, through moving and changing without origin or finality.[108] Following Harris, an elemental ecocriticism of fire emphasizes its transformative and fusing power, understanding it as a thing of hypnotic agency and unpredictability.[109] The examples of elemental thinking about fire by Macauley and Harris seem to make visible how we understand fire in mediated form. Instead of its endless transformative powers and its multiple shapes and stages, we have simplified fire by containing and domesticating it.

Both Macauley and Harris seem to draw attention to fire as an active, and 'living' thing. A similar understanding of fire has been important for its visual simulation. As described in the first chapter, Nguyen and Fedkiw differentiate between simulating water and fire by the characteristic of fire as an active phenomenon. Fire's active combustion process results in visually chaotic behaviour, described through properties as scattering, absorption and emission which results in visually complex shapes when fire emits light. To create an accurate simulation of fire, Nguyen and Fedkiw propose a method that allows for a level of control over this complex behaviour. This method models fire as an infinitely thin flame front which simplifies the combustion process by addressing it as a surface, instead of as a volume. Seemingly, when simulating fire, its multiple stages including its emergence, the smouldering, and initial combustion, are not in need of simulation to achieve a realistic visualization. Accordingly, where an elemental thinking of fire understands the phenomenon as active because of its multiple stages of transformation without a clear beginning or end, in simulation, this same understanding is achieved by eliminating those processes. Moreover, as explained by Bridson in

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[107] David Macauley, *Elemental Philosophy: Earth, Air, Fire, and Water as Environmental Ideas* (Albany: State University of New York Press, 2010), 38-40.

[108] J. J. Cohen and L. Duckert, ed., *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire*, 28.

[109] J. J. Cohen and L. Duckert, ed., *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire*, 312.

Fluid Simulation for Computer Graphics, these simulations describe fire through an assumption of a premixed flame. In this type of flame, the fuel and oxidant are mixed before the reaction, which differs from a diffusion flame where fuel and oxidizer are separated. This difference is worth mentioning because predominantly, fires are diffusion flames with great reaction whilst premixed flames have measurable flame velocity and a narrow reaction zone which results in "thin" flames.[110] Even though simulated fires often depict turbulent diffusion flames, they are described as premixed flames because this offers the needed simplification of the combustion process. Simulating fire using abovementioned method seems specifically useful for the visualization of Macauley's 'anthropogenic fire', a fire that we understand through the stage of its final flames, and which allows for control over its start and end. Seemingly, this is a different type of fire than understood through elemental thinking. Following Harris and Macauley, an elemental thinking of fire would consider the complexity and unpredictability of its transformations and movements and, the open burning of fire allows for mesmerizing and perhaps even connotations with magic. Other than simulated fire, such elemental fire is multiform, and its behaviour is obscured.

A thinking through air

In "Air as Medium", Eva Horn strives to make air visible again as a hybrid between human politics, scientific knowledge, and processes of nature. According to Horn, air is an object that defies its scientific objectification, and which signifies the matter of the immaterial. To address the complexities of air, Horn argues for an understanding of it as medium, instead of as matter. This requires a looking at air that is different from how it behaves, as is the objective of the natural sciences. In addition to air as an environment, Horn wants to shed light on air as a medium through a consideration of its historical and cultural functions as element of human knowledge. Such an epistemology of air can counter its conception as something standing outside of human experience, as a mere scientific object to be observed in the form of "climate" or "atmosphere". Horn argues that the externalization and objectifying of air is a

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[110] Sara McAllister, Jyh-Yuan Chen and A. Carlos Fernandez-Pello, *Fundamentals of Combustion Processes* (New York: Springer Science+Business Media, 2011), 111.

result of its translation into laws and computable mechanism used to model and predict its past, current, and future behaviour. Horn seems explicitly concerned with the 'scientific gaze' that enforces the distanced view of the human observer and nature as the observed object. Accordingly, the article argues that atmospheric science has always been guided by the modernist urge to predict and control unruly nature.[111] Addressing air through our cultural and aesthetic relationships with it, can possibly enable the difficult task of conceiving of air as an object of knowledge that immerses and shapes us. This experience-based approach shows how air is not separated from human memory, imagination, and the body. Making sense of air, therefore, needs to include the implicit and the fictional. Horn illustrates this by mentioning imaginative narratives that can possibly perceive air from "inside", or aesthetic manifestations and practices that focus on the medium's different forms of spatiality, scale, and temporality. Importantly, Horn mentions the need for a phenomenological approach that emphasizes the importance of considering an aesthetics and imagination of air, alongside its instrumentalized, scientific conception. Horn's conception of air as medium considers that, like other media, if air functions without disruption, it remains in the background of our perception. Therefore, we seem particularly aware of air when it performs a disruptive action, like when it storms or rains. However, Horn argues for a considering of air in all its sensory qualities, its (in)visibility, as well as its tactility, and dynamicity. This can also be done by considering the many historical ways in which humans have related to air through perhaps obsolete, or peculiar narratives and imagery. By considering these many different types of knowledges we can reach an 'aesthesis' of air that brings it back to the foreground of our perception.[112] In *Elemental Ecocriticism* a similar argument is made to consider air as multifaceted and dynamic, and not according to the human eye that perceives it as vacant. Rather, air is brimming with life forms that flow and swirl, and every change in air matters to earth, water, and fire.[113] Seemingly, an elemental thinking about air considers the qualities of the element as something that is filled, rather than empty, and tactile rather than merely elusive. It argues to consider air in all its sensory qualities. Elemental thinking through air renders air visible, through more than merely its

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[111] Eva Horn, "Air as Medium," *Grey Room* 73, (2018): 8-16, https://doi.org/10.1162/grey_a_00254.

[112] Eva Horn, "Air as Medium," 18-23.

[113] J. J. Cohen and L. Duckert, ed., *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire*, 311.

disruptions. The ‘fullness’ of air is also mentioned in the essay “Airy Something”, where Valerie Allen writes about turbulence as a place where many different realities and geometries of air collide. In the middle of turbulence, we can find a place of stability, a moment of zero that allows for doubt and speculation.[114] Accordingly, apart from merely making air visible, elemental thinking creates a depth in air. Such thinking imagines going ‘inside’ air and specifically, inside turbulence as this allows for imagination and speculation.

When using such elemental thinking about air to look at fluid simulation, it becomes evident that visual simulations of air merely consider our human perception of the phenomenon. As mentioned in the first chapter, simulating air alongside water or fire, requires too much computational power and therefore, it is only the illusion of the interaction between air and these other phenomena that is simulated. Accordingly, the visual behaviour that occurs when air ‘acts’ is visualized without considering any sensory qualities of air. Rather, what is considered is the visual change that occurs in water or fire, or in other phenomena on which air can act. Therefore, fluid simulations visualize air without translating the element into computation. Where water and fire become computational objects that can be acted upon and directed through fluid simulation’s (Navier-Stokes), air only exists as empty space without its own defining properties or assigned concepts. Seemingly, only when air acts as turbulence, it has the possibility of becoming a computational object. As turbulence creates the characteristic visual behaviour of interactions between air and other phenomena, it plays an important part in fluid simulation. However, the actual, unpredictable behaviour of turbulence is modelled through a procedural technique that allows for abstraction and simplification of its complexity. Air as turbulence is simplified to easily control its behavioural effect on other phenomena or objects. Therefore, air seems to only ‘exist’ in simulation as an effect, rather than an object on its own. An elemental thinking about air that considers air in all its sensory qualities and attempts to perceive air from inside seems impossible using fluid simulation. Simulated air has no depth or matter to enter and therefore, its manifestations are limited to an illusion of turbulence. Perhaps, the notion of an aesthesis of air, as proposed by Eva Horn can allow for imagining the translation of air into computational object. Questioning which properties would

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[114] J. J. Cohen and L. Duckert, ed., *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire*, 99.

need to be assigned to air as object, or in which ways it would possibly perform could allow for speculation on its tactility, and (in)visibility. This way, elemental thinking would enable a way of simulating air that does not centre around a human understanding of it as a mere 'visual effect'.

Conclusion on simulating the elements

This chapter introduced elemental theory through the work *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire* in which water, fire, air, and earth are addressed as dynamic entities that refuse objectification and translation into a human-knowable scale. The various essays in this work aim to make visible how each element carries many histories and cultural imaginations different from the normalized mechanistic models that afford and understanding of the elements as controllable resource. Accordingly, elemental theory argues for a thinking through the elements, which requires imagination and an engagement with the unknown by exceeding our humanly knowable scale. Such thinking about the elements has been useful for this thesis, as it shows ways of perceiving water, fire and air that do not consider the human, standing on the earth's surface, as the privileged position for making sense of the environment. To study fluid simulation, elemental theory is a valuable source for making visible how this technology is built according to such human-centred viewpoints to create realistic visualizations of the elements. By addressing elemental theory on these natural phenomena, this chapter aimed to show what type of imaginaries and speculations are theorized per element and how this might be applied to their methods of simulation. For example, in *Wild Blue Media*, Melody Jue shows how an exploration of the ocean as environment can destabilize terrestrial-biased experiences of space, time, perception and embodiment. Jue combines media theory and fabulation to imagine inhabiting environments like the ocean, or the sky through creatures like the vampire squid or the 'spherical being'. These examples show how our orientational language use and notions of embodiment are structured by our interpretation of the world whilst positioned at its surface. Similarly, in "The Sea Above", Cohen imagined the sky becoming sea to estrange us from our human understanding of space and to locate us at the meeting point of water and air where all things are in motion and there is no solidity like the ground of the earth. Accordingly, both authors think though the element of water to engage with the subjectivity of human perspectives in relation to the environment. By comparing such thinking through water with the descriptions of water through fluid simulation, it becomes specifically evident how this technology is built according to a terrestrial-biased understanding of the element. Jue's notion of 'surface dwelling' becomes apparent in the proposed method by Tessendorf to visualize ocean water according to phenomenological studies on the visual behaviour of its waves. Moreover, different types of equations are used for shallow and deep waters, according to their visual differences at the surface. These methods ignore things like currents and wind directions and solely use human observational data to create computational waters. Speculation on the inhabitation of such waters seems difficult, as the environment would lack the substance and environmental conditions that influence its embodiment. In a similar manner, the unpredictability and inherent chaos of the contact zone between water and air, as mentioned by Cohen, is erased from simulation in favour of behavioural control.

Examples of a thinking through fire seem to address a similar tension between the importance of thinking about complexity and chaos that occurs in combustion processes and the elimination thereof to achieve an accurate simulation. In the case of fire, authors Macauley and Harris both describe fire as an active, or even 'living' thing. This notion is shared by computer scientists Nguyen and Fedkiw that characterize fire as active phenomenon, differentiating it from water and air. In simulation, fire is modelled as a thin flame front that addresses the combustion process as a surface, instead of as a volume. The reading of elemental theory on fire showed the importance of recognising the multiple transforming stages of fire, from emergence to combustion, which are simplified in fluid simulation to the stage of the final flame. Moreover, even when referring to a diffusion flame, fire is simulated as premixed. To achieve accurate visual results, turbulence is added to make the flame appear chaotic, without simulating the chaotic behaviour itself. Accordingly, fluid simulations of fire seem to achieve an 'anthropogenic fire' as described by Macauley. Such a fire is one that we understand by perceiving its flames and of which we can control the start and end. Applying an elemental understanding of fire to simulation would include its unpredictability of transformation and therewith, unknowable actions.

Lastly, this chapter addressed elemental theory on air through Eva Horn's "Air as Medium" and the essay "Airy Something" by Valerie Allen. Horn's "Air as Medium" made insightful how air defies the "scientific gaze" that objectifies it, and which perceives it as something outside of human experience. Such externalization and objectification is caused by our understanding of air through the laws and computable mechanisms used to model and predict its behaviour. Rather, Horn looks at air as a medium and argues for an aesthesis of air to bring the element back to the foreground of our perception. An aesthesis of air requires a phenomenological approach that emphasizes all its sensory qualities, from its (in)visibility, tactility, to (cultural) imaginations and speculative narration. Unlike how we register air through human perception, it is not something empty. Rather, air is full of lifeforms and a constant swirling motion that changes earth, water, and fire. As mentioned in "Airy Something", this fullness of air becomes apparent in turbulence which is addressed by Allen as a place where different knowledges of air collide. In the middle of all its complexity, turbulence offers a place of stability that would allow for questioning and speculation. Accordingly, apart from making air visible, such elemental thinking seems to create a certain depth in air. It imagines going inside air and turbulence and to bring air to our attention, other than merely through its visual disruptions. When discussing fluids simulations of air, most apparently, air does not exist. As it is only the interaction between air and other phenomena that is visible to the human eye, air is simulated as a procedural effect, rather than a computational object. Where an object has built-in properties and dimensions to be acted upon, an effect is a description of a type of behaviour acted out by an object. Therefore, other than simulated water or fire, air is something that acts upon other things. Thinking about air as medium, as proposed by Horn, or thinking about turbulence as an environment, as mentioned by Allen, would require understanding air as having its own dimensions and properties, something that is filled, rather than vacant. Applying such thinking about air to simulation would allow for a questioning of what properties need to be assigned to air to turn it into computational object. Such a questioning allows for imagining ways in which air performs and acts apart from the visual effect of air that is registered by the human eye.

In conclusion, elemental theory can make visible how our thinking about the elements is influenced by a “scientific gaze” that turns these phenomena into objects to be picked and used as resource. Moreover, it shows how each element involves its own qualities and epistemologies. Interestingly, as fluid simulations are incompressible equations, water, fire, and air originate from the same basic, Navier-Stokes equations. Elemental theory, however, stresses their very individual qualities. The origin of fluid simulation in the scientific study of fluid flows makes its embedded scientific gaze evident. Nevertheless, as it has been adapted as tool for visualization for film and entertainment, artistic usage can possibly enable the expressive and imaginative conceptions argued for in elemental theory. Seemingly, there is a tension between the knowledge found in elemental theory’s phenomenological approach to the elements, and their scientific conceptions. As the elemental writings engaged with in this chapter primarily argue for a phenomenology of the elements to destabilize their normative scientific conceptions, they do not necessarily engage with how to join these different viewpoints. Comparing fluid simulation technology to elemental theory has shown that both are based on imagining the unreal, or the impossible, but with different results. As fluid simulation challenges the laws of physics to achieve realism, elemental theory destabilizes those same laws to create something unreal. Here we find a difference between the ‘usage’ of the elements and their representation. This difference is important to consider regarding fluid simulation, as is it concerned with “knowing how” scientific tools influence our conceptions of the natural environment, instead of merely “knowing that”. A “knowing how” is argued to create opportunity for the imaginative- and speculative usage of fluid simulation technology as it makes visible its guiding rules and structures onto which a user then can counteract, subvert, or tweak. Accordingly, elemental theory has pointed towards types of imaginative conceptions of the natural elements that can make visible our normative understanding of the environment. However, it does not necessarily engage with the role played by technology in the process of creating such conceptions. Therefore, the following, and last chapter engages with the work by Gaston Bachelard, a philosopher often referred to in elemental theory for his writing on water, fire, air, and earth, who also wrote extensively on the relationship between the natural sciences, everyday experience, technology, and imagination. In Bachelard’s work, the process of scientific- as well as imaginative thinking are considered ways to question and transcend reality as understood through perception. By aiming to reveal- and understand things unseen, the sciences and the imaginary can reveal reality anew. The elements serve as an example for Bachelard where the sciences, imagination and technology come together in a mutual process of sense making. Where previously discussed elemental theory primarily points out the phenomenological limitations of fluid simulation software, the following chapter argues that reading Bachelard allows for an additional understanding of the technology not as inherently limited but, rather, as taking part in the imaginative process itself. Accordingly, the last chapter uses the work by Bachelard to be able to specifically address technology and imagination as constituents of the scientific gaze. Bachelard's notions of 'material imagination' and 'phenomenotechnique' are used as framework to look at fluid simulation technology, as it shows the importance of studying the technological structures, the "knowing how", of technologies that influence how we conceive of the natural environment. Moreover, Bachelard's theory of imagination in combination with such an engineering perspective, can be used to effectively argue in favour of an imaginative, and expressive usage of fluid simulation technology. Following Bachelard's technical phenomenology, we can regard fluid simulations as instrument embodying knowledge of nature, and similarly, producing nature as a 'technophenomenon', an object designed for scientific study.

Chapter 4

Fluids and dreams: on the simulation of material imagination

Gaston Bachelard on the elements, science, and imagination

As was concluded in the previous chapter, discussing elemental theory on water, fire, and air helps question normalized conceptions of natural phenomena as objects to be objectively observed and controlled by humans. Such objectification of the elements is closely tied to what Eva Horn describes as the 'scientific gaze' which externalizes our natural environment. As was discussed through the work of Melody Jue, we have come to understand natural phenomena through epistemologies structured by a terrestrial bias and a habit of 'surface dwelling'. A reading of elemental theory alongside the research material on the development of fluid simulations of water, fire, and air was argued to make visible how such scientific-, and terrestrial biased thinking structures this technology. Moreover, the previous chapter argued that, even though elemental theory and fluid simulation both speculate on- and imagine the unreal to create different understandings of the elements, they do so with very different results. Where elemental theory uses fabulation to destabilize normative thinking about natural phenomena, fluid simulation technology speculates on our known natural laws to achieve realism. Pointing towards these differences seems most effective when discussing ways of representing the elements. As mentioned in the second chapter, film scholars like De Roo and Murphy argue for an 'elemental imagination' through otherworldly and speculative use of the elements in cinema to engage with abovementioned normative thinking about nature. Seemingly, fluid simulation could be especially valuable for such elemental imagination, since simulations can operate as realities on their own, unbound by physics or existing reality. However, as was argued, fluid simulations are structured by the goal of achieving realism and therewith, making expressive- or imaginative usage counterintuitive. Therefore, this thesis used the elemental theory as a framework to look at fluid simulation, to enable a discussion of the tension between such elemental thinking about water, fire, and air, and the epistemologies that can be found embedded in the mathematical translations of these elements.

This chapter aims to negotiate this tension through the work of Gaston Bachelard by arguing that Bachelard's work is especially valuable for a discussion of the role played by technology in our understanding of the elements. In the article "Gaston Bachelard and the Notion of "Phenomenotechnique"" (2005), historian of science Hans-Jörg Rheinberger emphasizes the relationship between scientific thinking and technology in the work of Bachelard. According to Bachelard, science produces objects as 'technophenomena' through scientific instruments. These technologies are not mere tools used by science, rather they are embodiments of acquired knowledge. Therefore, in modern science, technology is a theorem, something that problematizes an object, and at the same time gives it the shape in which we come to understand it. Following Rheinberger, in the work of Bachelard, phenomenon and instrument, science and object, concept and method are argued to be bound together in a process of mutual establishment.[115] Of specific interest for this chapter is the way in which Bachelard connects his theory of science with a theory on imagination. In his work on the elements, Bachelard conceptualized forms of imagination and their relationship to scientific thinking and everyday experience. Importantly, the author differentiates between something called 'formal imagination' and 'material imagination'. Following Bachelard, these two types of imagination are related to our knowing the world through scientific experiment, and the elements serve as exemplary phenomena illustrating his epistemology. Abovementioned notions of 'phenomenotechnique' and 'material- and formal imagination', are argued to be especially valuable for an understanding of fluid simulation through a "knowing how", rather than a "knowing that". In the following, this chapter uses Bachelard's theory on imagination to argue that the mathematical equations and technological structure of fluid simulation can be seen as its material imaginative qualities, hidden behind its formal imagery, as rendered output. It will be argued that using the notion of material imagination allows for the discussion of the unseen parts of fluid simulation software, namely its process of computation. The chapter discusses Bachelard's work on the elements such as, *Earth and Reveries of Repose: An Essay on Images of Interiority* (2011) and *The Psychoanalysis of Fire* (1964), and the author's work on philosophy of science, such as the abovementioned article by Hans-Jörg Rheinberger. Discussing these works shows how Bachelard blurs distinctions between scientific- and imaginative thinking, and technology in the process of understanding our natural environment. This perspective is argued to offer a valuable framework to look at fluid simulation as it allows for the study of this technology through the perspective of its usage and the process of computation, in relation to the way it produces knowledge as representation.

Formal and material imagination: fluidity of science

In *Earth and Reveries of Repose: An Essay on Images of Interiority*, Bachelard argues that modern science has reduced phenomena to 'rational entities' that can only be known experimentally on a human scale. The philosopher continues by arguing that we only see those

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[115] Hans-Jörg Rheinberger, "Gaston Bachelard and the Notion of "Phenomenotechnique"," *Perspectives on Science* 13, no. 3 (Fall, 2005): 320, DOI:10.1162/106361405774288026.

phenomena which are brought to light by scientific experiment. This has resulted in a passivity of vision that only engages with the surface of things rather than activating us to search beyond or within to understand the depth of nature. This is further explained by Bachelard with the argument that so many things live according to a rhythm of disguise and display. The showing and hiding of nature is used by the author to question the primacy of vision in understanding our environment. Rather, similar importance should be given to those things unseen and unknown, as is done to those that are revealed. Therefore, inventive imagination is as important as scientific thinking in revealing the unknown. By imagining that which is unseen, the philosopher argues that we can access an interior, material image, instead of the revealed, formal image.[116] Seemingly, Bachelard calls into question how science produces knowledge of reality. By its specific methods of revealing objects and phenomena, it discards theories and experiences that do not fit its ways of exposing and therefore, remain unseen. Imagination is argued by Bachelard to find more reality in what is hidden, than that which is shown. Accordingly, in this work, Bachelard claims that a truly knowing of things requires a combination of formal and material imagery; to account for what is perceived at the surface, whilst continue to search for those things that are hidden behind it, obscured from our normalized methods of sense making. What makes this process difficult, is that material images do not obey our known laws of signifying.[117] Therefore, material imagination is conceptualized as method to escape the simple reproduction of perception, whilst formal imagination deals with the surface of objects, their outside appearance through form and colour.

Following Bachelard, imagination is a way of deforming the images provided by perception, rather than a process of forming images. Furthermore, Bachelard calls imagination the “function of the unreal” which allows for the creation of new images instead of imitating what is given.[118] The value of imagination, therefore, is that it does not adjust to an existing reality but rather, changes and produces a reality functioning on its own terms.[119] This notion

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[116] Gaston Bachelard, *Earth and Reveries of Repose: An Essay on Images of Interiority*, trans. Mary McAllister Jones (Texas: Dallas Institute of Humanities and Culture Publications, 2011), 6-7.

[117] Gaston Bachelard, *Earth and Reveries of Repose: An Essay on Images of Interiority*, 20.

[118] Edward K. Kaplan, “Gaston Bachelard’s Philosophy of Imagination: An Introduction,” *Scienza&Filosfia* no. 8 (2012): 160.

[119] Edward K. Kaplan, “Gaston Bachelard’s Philosophy of Imagination: An Introduction,” 167.

reminds of the way in which Jordan Gowanlock differentiates simulation from media for representation, as explained in the second chapter. Rather than capturing an existing reality, simulation operates as a reality on its own. However, as was argued in the same chapter, simulation is geared towards the realistic mimicry of a film-based image of reality and therefore, its output relates to what Bachelard would describe as formal imagination. This chapter argues that when considering the output of fluid simulation as type of formal imagination, as concerned with the outer appearance of things, the computational process that produces this imagery can be seen as the material imagination. The mathematics and algorithms for simulation are hidden from the final output and as previously argued, are inherently abstract and fictional. Bachelard's theory on imagination offers a way of discussing the multiple layers of sense making through simulation; formally, through its outer appearance as film-based image, and materially, through its technological structure, the computational process. Bachelard uses the elements to argue that a process of understanding requires both formal, as well as material imagination. As mentioned in *The Psychoanalysis of Fire*, natural phenomena receive from us an immediate emotional response, through a multitude of sensibilities, often without us particularly noticing. However, we primarily understand the elements according to their representation as produced by perception and ordered according to physical law. Therefore, it is needed to take into consideration all sensory information, independent from bare representations that are supposedly true. The elements can allow for imagining things as not depending on perceived reality, and therefore not apprehended by knowledge. These phenomena are known by a combination of their formal imagery, their outer appearance, as well as a search for their material imagery by considering all sensibilities, conceptions and fictions that allow one to engage with the elements.[120]

Accordingly, for Bachelard, the natural elements exemplify the importance of imagination alongside normalized methods for understanding the world through representation and scientific reason. This resembles the use of imagination in elemental theory, as discussed in the previous chapter. However, what seems to differentiate Bachelard's use of imagination is the interconnectedness of technology, imagination, and scientific thinking in the process of

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[120] Gaston Bachelard, *The Psychoanalysis of Fire*, trans. Alan C. M. Ross (London: Routledge & Kegan Paul, 1964), 5.

understanding. Bachelard's theory of imagination speaks simultaneously about the image in the process of creation, as well as the image formed.[121] Therefore, this approach seems to allow for a further questioning of the process of creating knowledge, apart from merely pointing towards a contrast between scientific- and imaginative thinking. The work of Bachelard bifurcates into a philosophy of technology and science by revealing how science and its instruments reveal and therewith create reality, and a phenomenology of imagination and artistic creation. However, by addressing the elements these seemingly opposing forms of knowledge creation are found to be complementary to each other. By focussing on elementary imagination, the images and fabulations associated with earth, water, air, and fire, Bachelard sees how a scientific discourse has discarded those fabulations and replaced them by periodic tables.[122] Through the natural elements, the philosopher bridges processes of imagination and fabulation with scientific reason. Bachelard does this by showing how scientific signifying inherently allows for artistic- and imaginative creation because its empirical standards allow for deformation. Accordingly, imagination is facilitated by the scientific laws used to order the world, since a notion of real allows for imagining the unreal. It is not just the image that results from such fabulation that Bachelard is interested in. Rather, it is the process of spontaneity and freedom of arriving at such conceptions that is considered important.[123] Moreover, this process is argued to be valuable in order to question our settled habits of knowing and understanding. This conceptualization of processes for understanding, is what makes the work of Bachelard especially valuable for considering simulation technology. Reading Bachelard allows for the acknowledgement of the computational process of simulation technology as imaginative thinking.

By understanding the mathematics and the algorithms as material imagination, we can discuss the epistemologies and methods of sense making that are found embedded in this process. Arguably, following Bachelard's theory of imagination, the way knowledge is created

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[121] C. G. Chrisofides, "Gaston Bachelard and the Imagination of Matter," *Revue Internationale de Philosophie* 17, no. 66 (1963): 480-490, https://www.jstor.org/stable/23940344.

[122] H. Zwart, "Iconoclasm and Imagination: Gaston Bachelard's Philosophy of Technoscience," *Human Studies* 43 (2020): 62-63, https://doi.org/10.1007/s10746-019-09529-z.

[123] C. G. Chrisofides, "Gaston Bachelard and the Imagination of Matter," 488.

through simulation can be done by considering both its formal-, as well as material imaginative levels. Consequently, it requires a consideration of its process, a “knowing how”, alongside its outcome, the “knowing that”. As a technology inherently built according to scientific standards, fluid simulation can be seen as scientific instrument that reveals reality through mathematical equations. However, these equations have no direct relation to an existing reality. When analysing material imagination as an individual process of knowledge creation, we can understand fluid simulation software as inherently speculative and abstract. Rather than merely understanding it according to its formal imagery, as realistic output based on human perception, a focus on its material imagery offers an understanding which deforms such a reality.

Where elemental theory uses imagination in relation to the elements as means to reveal the scientific gaze, and therewith seemingly separates the two, the work of Bachelard rather shows how scientific- and imaginative thinking are complementary processes of knowledge creation. For Bachelard, the phenomenon, the technological instrument, scientific thinking and imagination are all joined in the process of understanding. Accordingly, Bachelard includes the technological instrument as part of the process of knowledge creation which offers an interesting addition to elemental theory, which mainly offered insight into the phenomenological limitations of fluid simulation. The work of Bachelard adds a focus on technology as taking part in a process of fabulation that combines imagination and scientific thinking. Moreover, for Bachelard, fact and fiction are closely related in the study of natural phenomena as the sciences measure and manipulate them as effectively as possible to study under controlled conditions. Therefore, science is seen as a technological, experimental practice by using instruments to produce simplifications of physical nature that are presented as facts.[124] According to Bachelard, these instruments are embodiments of learned knowledge, whilst simultaneously, they produce an object as ‘technophenomenon’. Therefore, in order to grasp the phenomenon to be known, one must understand the method of knowing. This relates to Bachelard’s notion of ‘phenomenotechnique’, where the philosopher extends phenomenology by accounting for the technological mediation on knowledge making processes. Through

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[124] H. Zwart, “Iconoclasm and Imagination: Gaston Bachelard’s Philosophy of Technoscience,” 67.

phenomenotechnique, one can understand how science realizes its objects, instead of describes what is already there.[125] Arguably, the technophenomenon can be understood as fact, as much as it can be understood as fiction. Bachelard's 'technical phenomenology' is argued to apply specifically well to technology and "knowing how" it creates knowledge.

Fluid simulation as technophenomenon

In "Gaston Bachelard and the Notion of "Phenomenotechnique"", Rheinberger explains Bachelard's phenomenotechnique as conceiving of technology not as a by-product of scientific experiment, but as a fundamental part of contemporary science. Accordingly, through phenomenotechnique, the sciences are addressed as particular ways of conceptualizing reality, in which technology forms the essential structure that helps arriving at such a conceptualization. Consequently, with this notion, Bachelard aims to show how technology is not a mere apparatus that helps find that which is given. Rather, technology creates a technically produced version of reality, that does not necessarily exist in nature. Therefore, what is perceived as fact, as derived from the real world, must be understood as the consequence of a discursive inquiry. The technophenomenon thereby, is a theoretical object, rather than something existing in the real world.[126] This understanding of the sciences is what leads Bachelard to argue that we must consider it as a specific way of experimentally creating knowledge and to study it accordingly. Therefore, it is important not to accept scientific outcomes as objective, but similar to Bachelard's conception of imagination, as a distinct form of creating knowledge of the world. This chapter argues that using the notion of phenomenotechnique in relation to fluid simulation, allows for an understanding of its method of creating knowledge of the natural elements. As a technology originally developed for scientific research but adapted for visualization purposes and artistic usage, fluid simulation seems to embed a combination of scientific-, as well as imaginative thinking. As mentioned in the first chapter, simulations of water, fire, and air are built according to the mathematical equations used to calculate fluid flows. Accordingly, these basic equations are theoretical

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[125] Hans-Jörg Rheinberger, "Gaston Bachelard and the Notion of "Phenomenotechnique"," 320-321.

[126] Hans-Jörg Rheinberger, "Gaston Bachelard and the Notion of "Phenomenotechnique"," 315-317.

models that explain physical processes in nature. Following Bachelard, such mathematical equations already require a philosophical reflection as technophenomena that create a notion of reality. Such a reflection addresses the scientific process of knowledge making and shows how it influences our everyday experience of the natural environment. Rheinberger calls this a 'process epistemology'; an epistemology of emergence and innovation.[127]

In fluid simulation, a visualization of reality is created by mathematical equations that are built according to a scientific rationale, but at the same time, are inherently speculative and fictional. Hence, a process epistemology of fluid simulation sheds light on its ways of using fabulation to create a film-based image of reality. This is seen in the example of simulating water through a method of surface modelling which disregards the influence of wind or currents to simulate waves as understood through human perception. The simulation of fire as a thin flame front, without accounting for its combustion process is another example of the imaginative use of scientific technology with the purpose of creating something that is perceived as existing reality. Therefore, a process epistemology of fluid simulation allows for considering its joined process of scientific- as well as imaginative thinking. I argue that a consideration of fluid simulation as technophenomenon can show how scientific- and imaginative thinking are not necessarily opposites, but rather supplement each other and therewith create space for the speculative usage of this technology. In fluid simulation the scientific laws of nature are used and tweaked resulting in unreal or seemingly impossible conceptions of the natural elements. However, as previously mentioned, to make this process of tweaking evident, an understanding of the computational process as its material imagination is needed. Such an understanding recognizes the final output as its formal imagery, and the 'hidden' process of creation as its material imagery.

Accordingly, a process epistemology of fluid simulation as technophenomenon needs to first account for the way in which mathematics are used to create a version of reality that has been accepted as truthful, which then allows for an understanding of how these equations are adjusted in a way that deforms or experiments with this accepted truth. Moreover, the procedural processes that are part of fluid simulation enable the fictionalized use of physical

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[127] Hans-Jörg Rheinberger, "Gaston Bachelard and the Notion of "Phenomenotechnique"," 318.

law resulting in a way of creating with computation that resides in-between automation and individual expression. Arguably, Bachelard's notion of phenomenotechnique and the philosopher's theory of formal and material imagination can be specifically valuable concepts to understand how visualizing natural phenomena using fluid simulation differs from representing these phenomena through recording or sensing, since it requires a consideration of the scientific-, technological-, and the imaginative processes of sense making that is embeds. Moreover, by addressing the method in which the technology creates conceptualizations of natural phenomena, instead of merely the process outcome as representation, we can question the ways in which it challenges or reinforces normalized conditions for observing or understanding these phenomena. As mentioned in elemental theory, to question the persistent objectification of the elements as resource to be observed and used by humans, we need to think through the impossible and the unreal to exceed their humanly knowable scale. By doing so, we can understand how a translation of water, fire, and air into mechanistic models obscures how the elements are entangled with each other, as well as with their individual affordances and cultural imaginations associated with them. Where in elemental theory, such imaginative thinking primarily seems applied to conceptions of the elements through storytelling and writing, the work of Bachelard allows for the consideration of such thinking in technological processes specifically. Perhaps, by means of Bachelard's technical phenomenology, we can study computation as a distinct way of creating narratives of our natural world, and therewith question which stories are easily told and which are made difficult.

Computational visualization and Bachelard's technical phenomenology

This chapter discussed the work of Gaston Bachelard on imagination and the notion of phenomenotechnique to bridge a supposed separation between scientific- and imaginative thinking. Such a separation seems to be found in the way in which elemental theory uses fabulation and imagination as means to counter normative, scientific conceptions that structure our ways of understanding the elements. Such imaginative thinking would allow for an understanding of the natural environment as exceeding a humanly knowable scale, whereas the sciences operate within the constraints of such a framework. In the work of Bachelard, however, the sciences seem to be conceptualized in an additional manner. Not merely as a way of translating natural phenomena into mechanistic models to be used and understood by humans, rather, Bachelard approaches the sciences as a peculiar way of understanding things, mediated by technology resulting in the creation of technophenomena. Following Bachelard, technology is a constitutive of the sciences and its outcomes should be considered as a specific form of reality. Bachelard uses this understanding of science to argue that it is the process of producing knowledge through scientific experiment that is important, rather than its factual outcomes. Studying the scientific process makes evident how it designs technologies that allow for the measuring and manipulation of natural phenomena. Accordingly, what is produced by science is a technical construct of things found. Rather than using imagination to oppose, or perhaps deform those technical phenomena, Bachelard argues that imagination is an inherent part of science and vice versa. Following Bachelard, the process of scientific research is inherently imaginative, as it deals with questions of the unknown and impossible. However, this process is no longer visible in its outcomes as facts. The author theorized this through his notions of 'formal-', and 'material imagination'. Where formal imagination is concerned with how things appear, as known understood through perception, material imagination searches for the unseen and the hidden. According to Bachelard, the scientific process is related to the process of material imagination, which can produce alternate and seemingly impossible worldviews by going beyond the appearance and into the depth of things.[128]

Scientific thinking, technological instruments, and imagination are interconnected in the process of creating knowledge of reality and it is in the natural elements that Bachelard finds this to become the most evident. Therefore, Bachelard's theory on imagination and philosophy of science is argued to be important for the expressive and imaginative usage of fluid simulation. As mentioned in the second chapter of this thesis, film scholars like De Roo and Murphy argue in favour of imaginative conceptions our natural environment which can be achieved by animation as it does not necessarily need to follow any physical law and is similarly not restricted to our settled ways of understanding. However, it is only when we look at the way in which this technology describes reality, that we can understand the importance of

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[128] H. Zwart, "Iconoclasm and Imagination: Gaston Bachelard's Philosopgy og Technoscience," 66-67.

expressive and imaginative use. Since these simulation technologies, like fluid simulation, are designed to visualize natural phenomena according to a pre-set understanding of reality, the process of creating with the technology becomes important as here, speculative, and fictional use can counter its tendencies for realism. Bachelard's process epistemology is particularly valuable here as it can make visible how imaginative conceptions are not found merely in the formal images produced, but in the search for the material imagery, the mathematical equations and algorithms of software that are hidden behind its outer appearance. For fluid simulation, Bachelard's theories of science and imagination makes visible how the process of simulating water, fire and air is both scientific- as well as imaginative through its tweaking of physical law into unrealities. The process of understanding fluid simulation through its scientific language, can allow for its expressive and imaginative use. Therefore, understanding scientific- and imaginative thinking as supporting each other, rather than opposing, could allow for the creation of alternate and speculative conceptions that question our settled ways of understanding the natural environment.

In conclusion, the work of Bachelard offers a valuable, additional viewpoint on the scientific gaze in relation to the natural elements as it points towards the influence of technology in creating knowledge, which is inherently scientific, as well as imaginative. I argue that such an understanding is important in the study of software and computation for visualization as it accounts for the epistemology of the process, rather than the outcome. As computation is both a scientific process as well as a process of manual manipulation, a focus on its embedded epistemologies and the actions that are performed with it, can make visible how it simultaneously shapes and produces knowledge. By knowing what understanding of reality is found embedded in the process of computation, we can question or subvert such conceptions to create realities anew. By studying fluid simulation according to its technological structure and development histories, alongside theory on the elements of water, fire, and air, this thesis reflects that a "knowing how" fluid simulation produces conceptualizations of natural phenomena creates space for its imaginative and speculative use.

Conclusion

This thesis looked at fluid simulation software, the technology used for the visualization and animation of natural phenomena like water, fire, and air. This software was analysed through a media archaeological approach, using theoretical frameworks ranging from media studies, computational science, philosophy of science and technology and elemental theory. As was stated in the introduction, software contains a complete process of ideas, research, and technical development, already before it performs in its final state. As many program languages are build-upon earlier versions, they can inform us on the specific problems that need solving through computation through time. Moreover, as the intended outcome of a software program only becomes visible when it runs, studying it by merely its technical aspects, or merely its visual outcome seems inadequate as the perceived outcome does not necessarily bear a referential relationship to the performing code. Therefore, this thesis specifically used a media archaeological approach to interpret computational systems as was formulated by Wardrip-Fruin in *Media Archaeology* (2011). This method proposes to look at the structures and processes of computation as a way of making visible the operational and ideological frameworks that influence its development, rather than focussing on a final output. Accordingly, such a media archaeological approach to computation aims to 'dig out' the preceding ideologies that have shaped current technologies. This approach was applied in this thesis by a discussion of the mathematical properties and technical development histories that structure fluid simulation software. By studying the computational process of visualizing natural phenomena through fluid simulation software, this thesis pointed towards an interesting tension that can be found between the epistemologies embedded in the mathematical descriptions of nature, originating from the natural sciences, and a thinking about these phenomena as offered through phenomenology and elemental theory. By engaging with this tension, this thesis shows how the technological structure of fluid simulation is steered by a rational, and instrumentalizing way of understanding the natural environment resulting in technology geared towards hyperrealism. Drawing from film-, and animation scholarship, it was argued how imaginative, and speculative visualizations of the natural elements can especially help question a normalized, human-centered understanding of the natural world. Accordingly, by making visible how such human-centered thinking can be found embedded in the technological structure of fluid simulation software, this thesis additionally aimed at a re-thinking simulation as representing an existing reality, and rather, understand it as inherently fictional, without bearing a relationship to an external world. This has been explained using the work of Gaston Bachelard and specifically, the philosopher's notions of 'phenomenotechnique' and 'material imagination'.

Before proposing such a re-thinking of the technology through the work of Bachelard, firstly, this thesis studied the technical structure and mathematical concepts of fluid simulation software through the ACM SIGGRAPH archive. The various research papers found in this archive, specifically the SIGGRAPH'04 course manual "The Elements of Nature: Interactive and Realistic Techniques," edited by Oliver Deusen (et al.), showed how algorithms used for the scientific study of fluid flows have been adapted for the purpose of visualization. This material gave insight into how fluid simulation software took shape over time and which concepts and numerical properties have been used to create realistic visualizations of water, fire, and air. As a highly influential research organization in the field of computer graphics, SIGGRAPH and its annual conferences, shape the direction of the technologies produced for computer graphics and visualization. Accordingly, the SIGGRAPH archive is an important source for studying the methods for computational visualization and, simultaneously, it makes evident the close ties between the fields of computer graphics, engineering, the natural sciences, and the arts. This exchange between these different field of research was also mentioned by Jordan Gowanlock in *Animating Unpredictable Effects: Nonlinearity in Hollywood's R&D Complex* (2021), where the author conceptualizes this relationship through an analysis of nonlinear simulation techniques for animation. Gowanlock argues that studying the development histories of nonlinear simulation offers insights in a specific paradigm of control that is shared between a multitude of fields using this type of simulation technology, ranging from animation and financial mathematics to climate science. *Animating Unpredictable Effects* shows how a new form of knowledge creation was produced by simulation techniques that consists of a programmable unpredictability, through the design of models that test a theory under pre-set conditions. Therewith, the work argues how simulation does not provide empirical knowledge, as coming from an existing reality, but rather, mimics a reality through testing and predicting. This understanding was applied to fluid simulation as a type of nonlinear system simulation. Importantly, even though Gowanlock makes clear how in many disciplines, nonlinear simulation is used to control- and exploit the unpredictable, the author similarly considers this technology as effective tool for imagination and speculation. Using this notion, this thesis argued that fluid simulation is a specifically interesting case since its embedded paradigm of prediction and control is used for the visualization of natural phenomena. Phenomena that are inherently unpredictable. Accordingly, to properly engage with the way in which the unpredictability of these phenomena is translated into mathematical equations, the first chapter addressed the basic equations that structure this technology, as well as the adaptions made for each specific element. This analysis was used to make visible how this technology visualizes nature according to human-centred viewpoints and orientation. Such an understanding was compared and contested in the third chapter by a reading of elemental theory. The most important insights offered by a study of the mathematical equations were the understanding that these phenomena are all calculated according to incompressible Navier-Stokes equations. This incompressibility means that each phenomenon can be calculated according to the same basic equations since their individual changes in are rarely registered perceptively by humans. Accordingly, as we do not perceive these changes, they can be disregarded from the equation. Moreover, general properties of speed, pressure, and viscosity are used to calculate and define fluids, which was argued to show how natural phenomena are simulated by properties that can be assigned a numerical value, and which can then be calculated according to a Cartesian coordinated grid. Therefore, fluid simulation visualizes the elements through a language that calculates them as objects, capable of static measurements in a pre-defined space, and according to pre-set time-units. Such an understanding of space according to Cartesian coordinates, and static measurements, makes visible how fluids are visualized according to an object-oriented paradigm that encounters natural phenomena as individual objects, abstracted, and detached from their context. Using the work of Alan J. Bishop mathematics, it was argued how such 'objectism' structures Western mathematics which instrumentalizes and generalizes through its notions of space, time, length, volume, and weight.

This object-oriented paradigm was also pointed out in relation to the commonly used Eulerian viewpoint that structures fluid simulation. This viewpoint works according to a predefined grid onto which an observer looks at the phenomenon. Accordingly, fluid simulations calculate and describe natural phenomena from a position located outside, and unaffected by them instead of being embedded within. Not only does this indicate a generalized understanding of human perception as the privileged way of knowing the environment, but it also shows how this technology calculates natural elements as if objects outside of our own living environment. This discussion of the basic equations was used to indicated how notions of instrumentalization, and an object-oriented paradigm dictate the mathematics that structure fluid simulation. Moreover, an understanding of the basic equations was argued to be important to discuss how each phenomenon requires specific adjustments and tweaks which offer valuable information on the individual characteristics that need to be visualized to perceive their simulations as truthful. For water, this resulted in a discussion of the air-water interface which is modelled in such a way that it can visually express the dynamic motion of rippling or splashing without actually simulating air. Moreover, the different visual behaviour of shallow versus deep waters were discussed. These examples showed how water is simulated according to the visual behaviour of its surface, as registered by humans. Knowledge on currents, or wind can be excluded from these equations, simplifying them by following a generalized understanding of how water behaves based on human perception. Specifically for fire, the complexity and unpredictability of the combustion process is simplified to be able to simulate the phenomenon according to a method modelling fire as an infinite flame front, disregarding the ignition process. Such surface-modelling of thin flames considers the aspects of fire we visually register and disregards the additional physical process. When discussing air, it became apparent that the complex and unpredictable shapes that produce visually realistic simulations of water and fire are modelled according to methods that tweak or neglect the physics that create this type of motion through air. As simulating interactions with air according to correct physical law would be highly complex, this type of movement faked to occur realistic through a process of procedural modelling. Accordingly, the details and complexities of turbulence created by air, are abstracted, and simplified to generate automated turbulent motion. This method of dealing with turbulent motion creates a process in-between computational automation and manual manipulation as parameters can be shifted and changed by the user. However, the concepts added to these parameters are pre-determined and the result of a process of abstraction of detail. Therefore, this chapter aimed to point towards a tension in the way in which this technology allows for artistic visualizations of natural phenomena, and the way in which it controls, and structures its possible usage. Therewith, it made clear how a practice of software archaeology can offer insights in the ideological frameworks that structure its research and development, and therewith shape possible processes of computational visualization.

To further understand how the technology for simulation structures it's possible usage, the second chapter engaged with the difference between simulation and other methods for visualization and representation, such as recording or sensing. As was explained in this chapter, where technologies for recording or capturing can create images or sounds of an existing reality, simulations need to build a reality from scratch. Unbound by known materials or dimensions, simulations operate as independent realities that can adapt and change according to user input and environmental conditions. However, as simulations often mimic reality as we encounter it through recording or film (the "film-based image"), we often understand them as offering a similar representation, namely, one based on a relationship with the external world. This chapter argued for the importance of understanding simulations not as representing an external world but rather, as representations of the specific rules and conditions that allows them to perform. This understanding allows for considering *how* simulations build realities, rather than merely what they represent. The importance of "knowing how", rather than "knowing that", in relation to simulation was explained by Gowanlock through the discussion of a philosophy of engineering. Importantly, discussing the rules and processes that structure a technology can make visible what type of actions and outputs it is geared towards, and which it complicates. In a similar line of thinking, Lev Manovich explains in *The Language of New Media*, that the development of physical simulation technology has been steered by the aim of achieving realism, which resulted in a restrictive representational output form. Importantly, following Manovich, this chapter explained that the development of simulation technology is steered towards a mimicking of the film-based image. Accordingly, to validate its worth in relation to film, computer graphics scientists have defined aspects of reality that needed to be simulated as realistically as possible to compete with the film-based image. Therefore, a simulated reality is inherently 'incomplete' as some objects, behaviours and effects are easy to create, whilst others are non-existent. Moving nature has been a primary case for proving computer graphics' capacities for realism. Fluid simulation, therefore, is one of those specific subjects where realism has been pushed in the development and design of the technology. Accordingly, this chapter argued that the goal of achieving realistic physical simulations, like fluid simulation, makes it more representationally restrictive as its built-in single-point perspective and photorealistic rendering no longer support the medium's ability of destabilizing our fixed ways of seeing and knowing.

This ability of challenging our fixed ways of seeing through animation was discussed through the work of scholar Pat Power. Building on the concepts of 'plasmatic' by Sergei Eisenstein, and the 'animorph' by Norman Klein, Power argues for the expressive usage of computational animation and simulation technologies to counteract against the realism that is favoured in the design of these technologies. The work by Power proved especially useful since it similarly engaged with the importance of a "knowing how" in relation to technologies for visualization and animation, as the embedded aim for realism is argued to make expressive, and abstract imagery counter intuitive. The importance of resisting the aim for realism in fluid simulation was argued for through the work of film scholars Ludo De Roo and Patrick D. Murphy, who argue that the natural elements specifically benefit from imaginative, and expressive imagery. These scholars mention that otherworldly conceptions and speculative use of natural phenomena can help question persistent binary oppositions between humans and the natural world. Moreover, imagination can offer disconnections with the cultural construct of the natural environment as a place "out there", instead of a living ecosystem that we are part of. Such an understanding of the natural environment as living force is best communicated through an (elemental) imagination. Accordingly, this chapter discussed that by operating as a reality independent from known material conditions, expressive, and imaginative usage of fluid simulation could especially facilitate a questioning of our settled ways of understanding of the natural environment. However, the goal of realism that structures the design of this technology makes such usage less obvious. Therewith, the chapter made evident how technologies for simulation mediate our understanding of reality differently from other media for representation, like technologies for recording or sensing.

To further understand what such imaginative conceptions of the natural elements entail, and how fluid simulation technology could enable-, or complicates such connections was discussed in the third chapter through a reading of elemental theory. As was explained, elemental theory aims to make visible how we have come to understand the elements through means of objectification and as controllable resources for commodity. The discussed works, *Elemental Ecocriticism: Thinking with Earth, Air, Water, and Fire* (2015), *Wild Blue Media: Thinking Through Seawater* (2020), *Elemental Philosophy: Earth, Air, Fire, and Water as Environmental Ideas* (2010) and “Air as Medium” (2018), all employ a way of imaginative, and speculative thinking to engage with an understanding of the natural elements that exceeds our humanly knowable scale. This chapter compared such elemental thinking about water, fire, and air, with the conceptualizations of these elements through computation as discussed in the first chapter. This comparison made evident how both elemental theory as well as fluid simulations embed imaginative conceptions of the elements that muddle with their normalized, scientific descriptions, however, serving different outcomes. As the imaginative thinking as practiced in elemental theory aims to destabilize normative ways of scaling and measuring the world according to a human-centred perspective, the imaginative conceptions of the elements through fluid simulation are argued to enforce such a human-centred perspective. As was pointed out in this chapter, fluid simulation differs from the “scientific gaze” as argued against in elemental theory as its specific ways of translating natural phenomena into numerical objects are not necessarily based on accurate physics. Rather, as seen in the first chapter, the scientific properties of the elements are adjusted and tweaked to achieve the needed visual results. Therefore, this chapter made visible a specific way of creating knowledge of these natural phenomena that resides in-between the scientific, and the imaginative.

Examples like Cohen’s ‘sky becoming sea’ and Jue’s ‘spherical being’ pointed out how our orientational language use and notions of embodiment are structured by our understanding of the world positioned at its surface. Such 'surface dwelling' was especially evident in the methods for calculating ocean waves and shallow waters through fluid simulation. By ignoring power exerted by air and merely modelling according to phenomenological studies on the visual behaviour of waves, fluid simulations describe imaginative water following human perceptual knowledge. Similarly, fire is modelled as a thin flame front, excluding its combustion process from the simulation. Therefore, only the outer appearance of fire is described through simulation, whilst especially the process of combustion is argued to stimulate an understanding of the element as complex by means of its many transformative stages. Lastly, a comparison was made between elemental thinking about air, and the conceptualization of air through fluid simulation. Interestingly, in "Air as Medium", air was argued to specifically defy the scientific gaze that objectifies it and perceives it as something outside of human existence. By arguing for an 'aesthesis' or air, Horn aims to bring air back to the foreground of our perception by engaging with all its sensory qualities. However, when discussing fluid simulations of air, it becomes evident that air is not calculated as computational object with built-in properties and dimensions that can act and change. Different from water and fire, air is described as a visual effect in the shape of turbulence. Accordingly, a consideration of all the sensory qualities of air including its tactility, (in)visibility and its qualities as environment hosting a multitude of lifeforms is made rather difficult through simulation. Simulated as an effect, such air is merely a description of a type of behaviour acted out by another object. Through these examples, this chapter made understandable how the mathematical concepts structuring fluid simulation erase complexity and ambiguity from these computational visualizations of the natural elements.

Accordingly, this comparison between elemental thinking about water, fire, and air and their understanding through fluid simulation shows a certain tension between the normalized scientific gaze that is made visible by elemental theory through imaginative thinking that exceeds our humanly knowable scale, and the way in which fluid simulation similarly speculates on such scientific thinking, but resulting in a reinforcement of such a human centred understanding of natural phenomena through vision. Where fluid simulations challenge the laws of physics to create realism, elemental theory destabilizes those same laws to create the unreal. This different 'usage' of the elements was argued to be important as it points towards the importance of a “knowing how” scientific tools influence our conceptions of the natural environment, rather than the merely “knowing that”. Where elemental theory has been effectively used to point out that scientific thinking influences our understanding and perceiving of natural phenomena, it does not necessarily engage with how such thinking is especially found embedded in technology. Accordingly, this thesis has pointed towards the tension found between mathematical descriptions of water, fire, and air, where nature is translated into controllable, and calculable object, and a thinking about these phenomena as offered through elemental theory, that aims to resist their knowing through human strategies for measurement and scaling. Where elemental theory was used to show how imagination can point out the scientific gaze that structures our understanding of the natural environment, the last chapter of this thesis turned to the philosophy of Gaston Bachelard, to argue that imagination and scientific thinking should not be considered opposite, but rather, are joined in a mutual process of understanding. According to Bachelard, the importance of imagination is specifically apparent when studying the natural elements, as these receive from us an immediate emotional response, often without particularly noticing. However, we precede to understand these phenomena primarily according to the concepts with which the sciences have ordered them. Through his writings on the elements, Bachelard developed a theory on imagination that joins the scientific gaze, technological instruments, everyday experience, and imagination in a mutual process of creating knowledge of our environment. According to Bachelard, the sciences and imagination are practices that are both factual as well as fictional, as they are concerned with the unknown, and the unseen. By questioning the simple reproduction of perception, science and imagination search for the things hidden behind their outside appearance. As mentioned in this chapter, Bachelard makes a distinction between a ‘formal imagination’, which deals with things as they appear, and a ‘material imagination’, which searches for those things obscured by the outer appearance, the hidden. As argued by Bachelard, a combination of both is needed to truly understand how normalized conditions for sense making influence how we perceive things.

Bachelard’s theory of imagination was applied to fluid simulation as incorporating both formal-, as well as material imagination. As was argued, the output of fluid simulations as realistic renderings of natural phenomena can be seen as a type of formal imagination, as the simple reproduction of perception. However, the mathematical equations and algorithms used to produce such imagery, bear no resemblance to an existing reality, and operate independently from it. Moreover, this computational process becomes obscured when output is rendered. Therefore, it was argued that material imagination can be found in the way in which fluid simulations fictionalizes reality through mathematics. Bachelard's theory on imagination was argued to be especially useful for the study of simulation, as it allows to address the process of how such a computational system creates knowledge of natural phenomena. This "knowing how" can further allow for a questioning of the normalized conditions for observing and understanding that are found embedded in these systems. This process was further elaborated upon through a discussion of Bachelard's technical phenomenology. Following Bachelard, through technology, the sciences create technically produced versions of things found, that do not necessarily exist in nature. The philosopher uses the notion of 'technophenomena' to refer to such things and to show how technology is not a mere apparatus, but an inherent part of the sense making process. Technology describes, as well as produces reality anew. This technical phenomenology was applied to fluid simulation as technical instrument to show how it embodies knowledge on natural phenomena, whilst simultaneously, by describing these phenomena through mathematics, produces them anew. As was argued through the work of Rheinberger and the notion of a 'process epistemology', Bachelard's work on imagination and philosophy of science show the importance of considering the process of producing knowledge through the scientific experiment, rather than its outcome perceived as fact.

This understanding argued to be specifically useful for the study of fluid simulation, since the technology is inherently built according to a scientific ordering of the world, and therefore, can be seen as a scientific instrument representing reality through formal imagination. However, a reading of Bachelard was used to show how material imagination can be found in the process of computation which only becomes evident when considering the "knowing how" of simulation technology. By applying a 'process epistemology', looking at the mathematics and technological structure, we can argue that fluid simulations are inherently fictional, whilst its output through realistic rendering obscures such an understanding.

Moreover, the notion of ‘technophenomenon’ was used to show how fluid simulation, is not merely a technology representing a film-based image of reality. Rather, fluid simulation as technophenomenon allows for its understanding as a theoretical object and should therefore be seen as a specific way of creating knowledge of the world. Accordingly, the work by Bachelard was used in this thesis to show how fluid simulations create a specific way of understanding natural phenomena by embedding scientific-, as well as imaginative thinking. Moreover, Bachelard’s technical phenomenology was argued to be especially useful for the study of simulation software and computational processes for visualization more broadly. Addressing software as a technophenomenon allows for a discussion of both its function as formal imagination, through its final output, as well as a consideration of the material imagination, the technological process. Moreover, using the notion of material imagination for simulation allows for an understanding of it as inherently fictional and speculative, rather than objectively describing an existing reality. Therewith, the last chapter made evident how the notions of material imagination and phenomenotechnique offer an effective framework for the consideration-, and usage of fluid simulation as technology for imagination and speculation.

Finally, this thesis followed the approach of a computational media archaeology, as formulated by Wardrip-Fruin’s, by ‘digging out’ the epistemologies embedded in a computational system through the discussion of its mathematical concepts, alongside theoretical frameworks ranging from philosophy of science and technology, elemental theory, phenomenology, computational science, and media studies. Such an approach aimed to offer an example of the study of software and computation according to the underlying ideas that can be found embedded in its systems, and therewith situating it as valuable object of study within the humanities. Moreover, using a media archaeological approach for the study of software can be seen as adding to its existing practice of studying technical components and/or other physical elements of media devices as it allows for the consideration of the non-physical properties of computation that are an equally important source for the ideologies and narratives that influence our usage and understanding of computational technologies. On that account, this thesis proposes future research in how software and computational processes for visualization embody knowledge on how we perceive and conceive of reality and, therewith, expand a practice of media archaeology by including software as intangible set of operating information that can be studied critically.

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