Non-Determinism in the Narrative Structure of Video Games

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Abstract

At the present time, computer games represent a finite interactive system. Even in their more experimental forms, the number of possible interactions between player and NPCs (non-player characters) and among NPCs and the game world has a finite number and is led by a deterministic system in which events can therefore be predicted. This implies that the story itself, seen as the series of events that will unfold during gameplay, is a closed system that can be predicted a priori. This study looks beyond this limitation, and identifies the elements needed for the emergence of a non-finite, emergent narrative structure. Two major contributions are offered through this research. The first contribution comes in the form of a clear categorization of the narrative structures embracing all video game production since the inception of the medium. In order to look for ways to generate a non-deterministic narrative in games, it is necessary to first gain a clear understanding of the current narrative structures implemented and how their impact on users' experiencing of the story. While many studies have observed the storytelling aspect, no attempt has been made to systematically distinguish among the different ways designers decide how stories are told in games. The second contribution is guided by the following research question: Is it possible to incorporate non-determinism into the narrative structure of computer games? The hypothesis offered is that non-determinism can be incorporated by means of nonlinear dynamical systems in general and Cellular Automata in particular.

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Introduction

I want a video game that tells me a different story every time I play it. I want a game that can surprise me and allow me to observe and be a participant of an evolving and continuous story, written by nobody, and emerging out of simple initial rules and conditions. I want a new kind of nondeterministic narrative architecture guiding my gaming experience. I want a story of which I am the sole, privileged actor and spectator.

These statements seem to be a most appropriate way to introduce the fundamental question guiding the study that lies ahead and represent the target subjects under investigation: video games and narrative structures. Furthermore, as a gamer and a researcher, I believe the desire expressed in these statements appears to be a legitimate and meaningful one to be sought at this point in time. From a global point of view, video games have become an established form of entertainment, spreading across all types of digital and electronic platforms. They have captured the attention of academic scholars and represent the subject matter of a growing and multidisciplinary academic research.

Since its inception more than half a century ago on machines long forgotten which are hard to imagine today in the digital age, the medium of the video game has undergone a constant and exponential development and can today count many achievements. From their initial experimental(but revolutionary) steps as simple monochrome dots and blips moving on a cathode-ray oscilloscope, video games are today capable of offering vast threedimensional worlds, freely navigable and populated by life-like characters or human players in the persistent game worlds of MMORPG (Massively Multiplayer Online Role Playing Games). Once relegated to the curiosity of adults in the arcades, and subsequently appealing mostly to young audiences through the first generations of home consoles, video games have today imposed themselves on the mass entertainment market generating sales and revenues that regularly rival and surpass those of the movie industry. Mature themes have long become integrated in game design, reaching audiences of all ages, with gameplay and story content seeking to engage players on a wide range of entertainment levels, from the intense action-driven experience of the fictional global war conflicts in *Battlefield 3* (DICE, 2011) to the more intellectually-oriented and slow-paced setting of a desolated island in the Hebrides in

Dear Esther (The Chinese Room, 2010) or the embodiment of Ayn Rand's doctrine of Objectivism as expressed in *Atlas Shrugged* (1957) combined with the existence of multiple realities through the phenomenon of quantum entanglement in the *Bioshock* series (2K/Irrational Games, 2007-2014).

From the technical point of view, most of the components pertinent to game design have witnessed significant advancements. Design elements such as sound effects, voice and music, graphics and character models, number of NPCs (non-player characters) and AIcontrolled units at once, as well as the size of game worlds, gameplay longevity and user interface have been constantly refined, their boundaries being constantly pushed so as to take full advantage of the increase of processing power available in computers. The online component is also being constantly expanded allowing players to cooperate in a large variety of multiplayer modes and to share their game sessions, scores and achievements instantly with millions of other players. In the graphical department, the pixelated monochrome beginnings of *Pong* (Atari, 1971), the two dimensional static worlds of *Space Invaders* (Taito Corporation, 1978), *Pac-man* (Namco, 1980) or *Super Mario Bros*.

(Nintendo R&D4, 1985) with hand-drawn, cartoon-style characters, and the rudimentary 3D graphics of a heavily polygonal Lara Croft in *Tomb Raider* (Core Design, 1996) have eventually paved the way for fully-voiced, photorealistic character models portraying accurate facial and bodily animations, with behaviour approximating human credibility, and living in detailed dynamic environments governed by accurate physics engines. Facial animation technologies capable of conveying state of mind and emotions, featured in titles such as *Heavy Rain* (Quantic Dream, 2010) and *L.A. Noire* (Team Bondi, 2011), appear convincing enough to devise, for example, gameplay objectives revolving around players understanding NPCs mood and emotions through their facial expressions and taking decisions accordingly. Likewise, dedicated engines such as Euphoria, are gaining ground in simulating the human central nervous system in order to endow NPCs with credible motion and impact reactions and environments can today enjoy convincing lighting, simulations of fluid dynamics and 24/h day cycles. While the graphics compartment has been given prominence and, after the introduction of 3D, has seen the most advancements, aspects such as user interface and controls have also been subject to significant innovations, with the introduction, for example, of motion sensing technologies, initially introduced by Nintendo on the Wii system, and later also adopted by Microsoft and Sony with the Kinect and the

PS Eye and Move, capable of reading with increased accuracy the player's movements and translating them into real-time on-screen actions. In short, from an audio/visual and interface perspective, games have witnessed a constant line of improvement and transformation, sometimes in harmony with players' demands, other times catching them by surprise.

Nevertheless, other elements in game development, such as narrative structures and AI techniques, regardless of the varying degree of importance given at different times in the design process, have not witnessed significant qualitative innovations. On the contrary, it is safe to say that AI and narrating techniques have maintained a steady state for decades. Apart from quantitative changes dependent on the increasing storage capabilities and processor calculations of computers, and careful fine-tuning of conventional architectures, these two aspects appear in games today in essentially the same form, if slightly refined, as titles developed one or two decades ago. Game narrative structures, defined here as the methods and techniques through which the story content of the game is delivered, while displaying several degrees of sophistication, can be grouped into four distinct categories which have remained as such throughout the history of video games. Illustrated through a detailed explanation later in this chapter, this classification derives from the necessity to bring understanding on what is currently allowed by game architectures in terms of storytelling, and to look into the future to see what types of changes would be needed to innovate on narrative structures and what this would imply for narrative in general. While they can offer a diverse story experiencing for players, we will discover how all narratives in games are deterministic. Simply put, all stories in video games are composed beforehand, unfold through a pre-established design and their branching and endings, multiple though they can be, whether direct or incidental, are finite and can be predicted. Multiple playthroughs will eventually lead to a saturation point where all story variations repeat.

To return to the initial statements, a game that tells a different story upon every game session needs a design that addresses the deterministic nature of narrative structures. This turns the attention towards the Artificial Intelligence used in video games, as a different type of narrative structure would rely on the behaviour of NPCs and game world, elements which are governed by the invisible hand of AI. Until now, most game AI techniques have primarily revolved around deterministic systems offering designers acceptable levels of control and predictability for agent behaviour. With the exception of a few titles such as *Creatures* (Grand, 1995) or *Black&White* (Lionhead Studios, 2001), pre-established scripted events are prominent and eventually lead to a finite number of possible interactions and agent behaviours. Yet a shared thought among game AI developers indicates how AI is performing under par compared to graphics, sound and level design and that its innovation is the next step in game design and has the potential to revolutionize the very nature of video games.

Therefore we ask ourselves: where do video games go from here? Over the years they have become bigger, longer, more interactive and beautiful to behold. They have captivated large audiences and captured the attention of scholars. Yet, their structure has fundamentally remained untouched, with the last qualitative transition being the introduction of 3D and freely navigable environments. A point has been reached where the next generation of games looks like a slightly more embellished iteration of the previous one, offering an unchanged gameplay experience and the same storytelling structures. In this moment of uncertainty for the future of video game design, this study offers a close examination of narrative structures and game AI. These two fields not only provide room for change and improvement, but also hold the promise, for the next qualitative innovation for both video games and narrative in general.

In order to satisfy the desire expressed in the initial statements, the main question guiding the present investigation will be whether or not it is possible to incorporate nondeterminism into the narrative structure of video games. A hypothesis will ensue proposing that non-determinism can be incorporated by integrating elements from nonlinear dynamical systems in general, and Cellular Automata in particular with game AI architectures. The study will unfold by first understanding the definition and history of video games and the development and increase of importance of its narrative structures. These will be classified into four distinct categories, understanding their mechanics and limitations. The nature and definition of narrative will be explored in order to understand how video game storytelling systems adhere to it and it will be shown how this very element simultaneously divided scholars and promoted a fruitful academic research. The attention will then shift towards the nature of determinism and its role in narrative and game design. Examples of non-linear dynamical systems and Cellular Automata will be examined, and a model integrating them with game

AI will be proposed and discussed, with a final reflection on what its implications will be for games and their impact on the public and the nature of narrative as we know it.

In 2004, media scholar James Newman predicted that the future of games would lead the medium to embrace the online dimension, and proliferate on mobile platforms through casual games. He also considered the growing attention given to retro-gaming -the discovery and revamping of classic titles primarily through software emulating the original consoles and platforms. It is safe to say that in 2013, games have increasingly taken advantage of online and sharing components, and the proliferation of mobile casual titles is but a fact. Interest in retro-gaming, however, was already popular during the 16bit and 32bit console era, with old classic from the ATARI 2600 console being emulated on the first Playstation, and the first museum dedicated to video games, Videotopia, opening in Pittsburgh in 1996. Retro-gaming is still alive today, having consolidated into its own game genre. What to look for now? With games having become more realistic, more artistic, culturally more significant, with online communities counting millions of gamers, and with a keen eye on their past, what promise do they hold for the future? Non-determinism is one possible direction, and it will be explored throughout this study.

Chapter 1. Nature, History and Narrative Structures of Video Games

1.1 United in its Diversity: Defining the Medium of the Video Game

Before understanding how video games were born, how they evolved, what their limits are and what the future holds for them, it is of primary importance to elaborate a definition. This derives not only from the necessity of bringing clarity to the various terminologies used, but also serves as a reference to distinguish the object under scrutiny from other forms of media. The reason why defining video games appears more problematic than, for example, defining theatre, films or picture books, lies in their very nature, and, as understood through the remediation notion discussed by Bolter and Grusin (1999), their capability for absorbing features from other media into their unique format. Bolter and Grusin indicate how 'the whole genre of computer games like *Myst* or *Doom* remediate cinema' with a conclusion that 'players become characters in a cinematic narrative' (341). Bolter and Grusin identify a key aspect of video games in their chameleonic nature, their ability to reproduce on the screen virtually all forms of media. It is this very ability which makes it problematic to define games according to the form they take on the screen and the content they provide. When Newman asks whether we should see games as 'continuations of other media such as films or television' or 'hybrids of both' (2004; 10), or when Murray discusses the potential of games as expressive new platforms for narrative and drama (1998), it becomes apparent that attempting to determine the nature of the medium through its output would generate no consensus. While Wolf suggests that video games 'are best approached…using conceptual tools developed in film and television theory and media studies' (1997; 3), Frasca (2003; 3) reminds that games are primarily simulations, while traditional media are representational. He explains how a plane landing in a film is 'fixed and unalterable', while landing a plane in a flight simulator is subject to the player performing 'actions that modify the behaviour of the system' (3).

Why, as emphasized by those who attempt an academic study of video games, is there difficulty in defining the object of the research? Two factors come to mind. The first reason is linked with video games being, as Wolf puts it, ‘a text [which] is much harder to master’ (1997; 7). Indeed, time, skills, patience and equipment are needed to explore one game title in its entirety. A first-hand experience with the medium will require the researcher to complete tasks, solve puzzles and overcome challenges to reach the end of the game. As games encourage replay, multiple playthroughs (completion of the game) will often be required to explore alternative storylines, uncover hidden areas/levels and understand all the possible interactions with the game world and also experience the multiplayer side if present. Simply put, no analysis of a game will be deemed accurate unless all the above activities have been carried out. The time needed to complete a modern story-driven title may range from six to sixty hours of gameplay, with an analytical approach easily doubling such duration. Merely observing a few sequences of the game, or playing the first sections would only lead to a superficial, inaccurate understanding of what the game has to offer. Certain titles, like *Final Fantasy XIII* (Square Enix, 2009), may not reveal all of their features at once. The latest entry in the popular RPG series alternates a very linear introductory phase of an average length of 15-20 hours, to a more open-ended, free roaming experience that becomes possible half-way through the game.

The second reason comes from the fact that games widely vary in visual styles, contents, modes of interaction and purposes. They can embody elements of painting and photography, provide material for narrative and literature, take the shape of interactive movies, offer accurate simulations of physics and represent fertile ground for Artificial Intelligence and models of nonlinear dynamical systems. Video games can also be occasionally employed for military training purposes, passenger jet flight training, history lessons and to promote learning in general. Their field of application also extends to therapeutical experimentation, helping cancer patients, for example, understand the management and nature of chemotherapy side-effects (Bruggers et al., 2012), or aid burn victims manage pain during wound care and physical therapy (Sharar et al., 2008; Hoffman et al., 2000).

As video games take advantage of the advances in computing technology, adding more depth to their story content, gameplay and audio/visual representations, they provide, following Wolf (1997; 7), ‘more opportunity to embody a message, world-view, or philosophy into a game the same way these elements can be incorporated into novels and films’. Game designer Yuki Ikeda speaks of his wish to express the emotions embedded in the experience of getting lost as a child through rainy, desolated urban environments in the upcoming title *Rain* (Acquire SCE Japan Studio, 2013). The trilogy of the first person shooter *Bioshock* (2K/Irrational Games, 2007-2013), for example, offers players a portal into the fictional cities of Rapture and Columbia with a narrative setting shaped after Ayn Rand's philosophy of Objectivism. The *Assassin's Creed* series (Ubisoft, 2007-2013), instead, introduces the historical fiction genre by attempting to accurately recreate historical environments and casting players in the midst of documented events occurred in the past. *Rome*: *Total War* (Creative Assembly, 2004) provides players with a strategic approach on the Roman army with the possibility of controlling the tactics of hundreds of units to determine the outcome of famous historical battles and the empire's expansion. The *God of War* series (Santa Monica Studio, 2005 - 2013), instead, drawing from Greek mythology, adopts the one-man army option, placing its character Kratos in battles against a mix of mythological creatures and against the gods of Olympus themselves.

From a visual perspective, on the other hand, Playdead's two-dimensional side-scroller *Limbo* (2010) adopts a minimalistic, hand-painted artistic style with prominent black and white palettes to create a disturbing horror atmosphere reminiscent of films from the German Expressionism such as *Nosferatu*. Similarly, film noir atmospheres featuring darktoned colours and nightly environments are prominent in the first two chapters of *Max Payne* (Remedy Entertainment, 2001-2003), and are accompanied by long soliloquies from the protagonist celebrating his cynical and disillusioned attitude. Artistic diversity can be observed in *Okami*'s take on Japanese folklore (Clover Studio, 2006), rendered through the traditional Japanese sumi-e ink and wash paint style, or in the vibrant colours of *Flower* (thatgamecompany, 2009), with players guiding a flower petal by controlling the wind and restoring life to the landscape. Games may follow the episodic format of TV series, as in *Resident Evil Revelations* (Capcom, 2012) or *Forbidden Siren* (Project Siren, 2003), with each episode beginning with a summary narration of the previous one, or adopt the a first or third person "found footage" camera perspective, as in *Kane & Lynch 2: Dog Days* (IO Interactive, 2010) or the more recent *Slender: The Arrival* (Blue Isle Studio, 2013) and *Outlast* (Red Barrels, 2013). *Just Dance* (Ubisoft, 2009) simply asks the player to dance in front of the screen, while *Rocksmith* (Ubisoft San Francisco, 2013) will let players plug and play an electric guitar. At the same time, also embracing under the category of video games casual titles developed for mobile platforms such as *Fruit Ninja* (Halfbrick Studios, 2010) and *Angry Birds* (Rovio, 2009), purposefully devoid of content and based on pure hand-eye coordination and reflexes, appears acceptable and unproblematic.

The great diversity observable in video games is not, however, a recent phenomenon. The early versions of *Colossal Cave* (Crowther, 1976) and *Zork* (Infocom, 1980) were adventure games based entirely on a text-based interaction with a language parser, and while considered by some (Bakie, 2011; 18), (Herz, 1997; 27) as video games and precursors of the graphical adventure genre first appeared by Roberta and Ken Williams' *Mystery House* (On-Line Systems, 1980), they are also approached as interactive fiction and envisioned as an expansion of literature, as in Montfort's *Twisty Little Passages* (2005). Likewise, *Dragon's Lair* (AMS, 1983) appeared in the form of a full interactive animated movie, requiring players to primarily watch pre-recorded scenes and execute specific commands during key moments, with the entire process recently becoming an established gameplay element in many of today's titles known as QTE (Quick Time Events). Sega's *Comix Zone* (Sega Technical Institute, 1995) takes the format of a comic book, with the protagonist moving across panels accompanied by talk bubbles and with each level consisting of two pages. In short, the final appearance of a game depends on factors such as the designers' inclination to recreate specific visual styles drawing on other media. It depends on their intention to convey specific messages or generate particular gameplay experiences for the players. Being perhaps the medium with the highest degree of communication between authors and audience, the video game is also the end result of designers listening to players' feedback. It is not uncommon to observe designers discussing directly with gamers about the content and gameplay of future projects, about flaws of previous games, and about improvements in general in online dedicated forums.

Designer American McGee's blog www.americanmcgee.com (2012) is an example of a space where authors and players share opinions, ideas and criticism. Important phases of game design, especially before the release of high production titles, are dedicated to players' feedback and level of satisfaction and entertainment during the so-called alpha and beta testing, when there is still room for improvements and modifications. While these most often regard gameplay elements, debugging and fine-tuning of AI, revisions of the story content of the game can also occur. The recent title of *Mass Effect 3* (BioWare, 2012), the latest entry in BioWare's science fiction role-playing series, generated dissatisfaction among gamers regarding its ending, considered by many unclear and unsatisfactory. Fierce criticism and continuous requests from players who had an emotional investment towards their own character and the story finally led designers to re-write the ending and release it as a free DLC (Downloadable Content). Similarly, the “Kickstarter” crowd funding project, started in 2009, offers gamers the chance to directly participate in the designing of a video game, by allowing them to fund and thus help the development of independent designers’ game proposals.

In the light of this great diversity of themes, purposes, visual styles and types of interactions as the end result of authorial intent, market trends and players’ voice, defining the medium of the video game means primarily identifying a number of aspects that are unique to the nature of the video game and transcend the tangible differences. Three terms can be distinguished to characterize the medium: play, game and video. Influenced by Huizinga’s *Homo Ludens* (1944), in *Les Jeux et les Hommes:le masque et le vertige* (1958), French sociologist Caillois identifies the universal aspects of play and game as observed among humans through the concepts of Agon, Alea, Mimesis and Ilinx. Respectively corresponding to the notion of competition (Agon), randomness (Alea), role play (Mimesis) and motion (Ilinx), these characteristics lie at the heart of video game design and video game playing experience.

The competition, embodied by AI opponents, human players or implicitly by the game system itself in the absence of tangible opposition, as in *Tetris* (Pajitnov, 1984), emerges even in titles that present no immediate challenge but presuppose an ending and therefore a series of tasks to complete or checkpoints to trigger. The calm, explorative first person experience of *Dear Esther*, for example, while presenting no apparent challenge, still requires players to reach specific locations on the island to trigger a narrating voice and will eventually combine together all the storyline bits uncovered during the navigation. When playing against the CPU, the element of randomness is embedded in the AI architecture of the game and directly linked to the element of challenge. It ensures that repetitiveness is minimized and is used to promote diversified enemy unit behaviour in an attempt to maintain a balanced sense of difficulty. As Newman notes, the ‘unpredictability of the sequence of falling blocks ensures that *Tetris* cannot be simply “learned” ‘(2004; 22). The notion of Alea reaches its full realization in games when playing in cooperation with or against other human players. As we will see later, complete randomness and unpredictability are still concepts not yet fully implemented in game design and often avoided. Even in *Tetris*, the shape of the falling blocks is not determined by a full random generator, but by a “fair” algorithm that generates four sets of seven blocks ahead of time and ensures that players receive a balanced number of all types of blocks. Yet, common deterministic techniques used in games such as Fuzzy Finite State Machines (FFSM), Behavioural Trees and Artificial Neural Networks are very important to diversify the gaming experience when playing against the CPU.

The next two elements of mimesis and ilinx are also deeply embedded in the video gaming experience. From RPG titles, with players able to customize their avatar’s appearance, skills and even personality traits to their liking, to First Person

Shooters/Adventures where players’ immersion in the game world is enhanced by the first person perspective, mimesis and the adopted persona, in the form of a single or many fictitious characters are deeply interconnected in all games offering any type of narrative setting. Furthermore, interpreting mimesis along the lines of imitation, mimicry or simulation, reveals the fundamental nature of this element in game design, from the moment that all games offer an alternative version of reality, what Caillois refers to, as indicated by Perron (2012; 85), as ‘a free unreality, as against life’. Finally, the ilinx, which Caillois refers to as kinaesthetic pleasure derived from physical movement during the play activity, and which Newman (2004) and Friedman (1995) link directly with the engagement with the game interface, represents another basic quality of video games and emerges in the form of players’ interacting with the game world by means of manipulating a controller. Whether in titles requiring fast hand-eye coordination, or during slow-paced navigational gameplay, movement translating into interaction emerge through the vast majority of games, in more traditional forms by pressing keys on a joystick, and more innovative ways by moving in front of an integrated camera detecting physical movement. Newman (2002b) approaches this feature as one of the distinguishing qualities of video games, seen in this light as an ‘embodied experience’ (2004; 27).

Finally, the notions of Ludus and Paideia, understood as structured rule-based and unbounded gameplay, represent the playground where the four elements intrinsic to play and games occur. Frasca (1999) indicates how paideia leads to contexts in which there are no set objectives, and players are free to interact with the game world according to their own terms. Sandbox games such as *Red Dead Redemption* (Rockstar San Diego, 2010) or *Sleeping Dogs* (United Front

Games, 2012) provide large game worlds specifically designed to promote unrestricted play, while other titles from other genres can also occasionally offer some form of free mode. However, ‘as soon as the *paideia* player determines a goal with winning and losing rules, the activity may become a *ludus*’ (Frasca, 1999).

The elements explored above can contribute to elaborate a definition of video games which contains qualities universal to all game titles and helps identify the true nature of the medium beyond content, purpose and modes of representation. We can therefore define the medium as:

an interactive entertainment software system requiring players to interface with a game world displayed on a screen and perform actions in cooperation with or against AIcontrolled/human agents in a task or competition-based activity.

As for the differences in the terminology of computer game or video game, nowadays the difference is no longer relevant, as all games are normally developed on computer systems and then re-adapted to the target platforms, which may be home consoles, portable dedicated consoles, mobile devices or online networks, all of which are also based on microprocessor and computer architectures. However, while computer games may represent a sub-category of video games played exclusively on PC platforms (Newman, 2004; Wolf, 1997), using the term video will eliminate possible confusion as by video it will be meant the output method through images on a display. With a clearer concept of what the video game medium is, it becomes possible to trace both its history and its directions for the future. It becomes possible to understand, as we will see, the consolidation of narrative structures and most importantly, their role in game design and gaming experience and finally how the hypothesized nondeterministic model capable of generating emergent AI unit behaviour and narrative structures finds its place among the universal components of video game design.

1.2 A Sixty Year-old New Medium: A Brief History of Video Games

“I have no memory of a world devoid of colored dots chasing each other across a screen. I was toggling a joystick before I learned to read, mastered *Breakout* stratagems before memorizing the multiplication table, conquered *Asteroids* before solving the mystery of long division” (Herz, 1997; 1).

Born in 1971, the same year as the first coin-operated video game, designed by Nolan Bushnell, *Computer Space* (Nutting Associates, 1971), J.C. Herz starts her take on the history of video games by recounting her early childhood populated by the first TV game console and the gradual appearance of arcade machines. One year later, the first video game company is founded under ATARI Inc. by Nolan Bushnell and the first successful game is launched into the market, *Pong* (1971).These are the years when video games, which had actually debuted decades earlier in various contexts and did not take off, make their first global impact as a new entertainment activity and start carving a niche into the global culture that has expanded and grown in importance to this day. In the historical profile on video games, Herz, attributes the birth of commercial video games to *Computer Space* and *Pong*. It is generally accepted (Wolf, 1997 and 2008; Donovan, 2010) to trace the origin of the video game industry to these two titles, as they constitute the first examples of games designed with a global audience in mind and with a commercial objective. Their merit consisted in making accessible to the public ideas previously developed by William Higinbotham and Steve Russell. Considered as the forefathers of video games, their prototypes contributed to show the potential video games would have as a recreational activity by generating interest at the local level, although they were born as experiments devoid of commercial purposes.

Working at Brookhaven National Laboratory, Higinbotham ‘had a brainstorm’ (Bakie, 2011; 4) for the upcoming annual exhibition in 1958, and thought of creating an interactive screen to stimulate the interest of the visitors. His ideas took the form of *Tennis for Two*, an interactive tennis game displayed on an oscilloscope from a side-view perspective, and benefitted from Higinbotham’s calculations of missile trajectories to control the movement and bounces of the ball. The analog computer used to display the simulation incorporated instructions on how to simulate trajectories of a moving object such as missile or bullet, and

Higinbotham 'made the leap allowing two people to volley a bouncing ball' (Bakie, 2011; 4) by means of a directional controller with a single key. While, Higinbotham's experiment was not the first of its kind, the breakthrough came from the fact that for the first time a video game was presented to a general public. As cited in Donovan (2010; 9),

Higinbotham remembers how 'high schoolers liked it best, you couldn't pull them away from it'. Yet, after being exhibited the following year, the project was forgotten and the game was dismantled. This false start was preceded by another failed project by American TV network Dumont in 1947. Exploring the possibility of interactive games on TV set, two employees of the company, Goldsmith and Mann, devised a Cathode-Ray Tube

Amusement Device. Based exclusively on internal electrical circuitry, this device simulated missiles being fired at a fixed target. As Donovan explains, however, 'Dumont never turned the device into a commercial product' (2010; 9). In 1952, while writing his PhD thesis on human-computer interaction, Douglas programmed what can arguably be considered the first video game employing a computer AI algorithm competing against the player, known as *OXO*. Taking advantage of EDSAC computing machine at the University of Cambridge, the game was a simulation of noughts and crosses displayed on a CRT screen, with the user being able to use a telephone dialer as input device. His work, however, remained an isolated demonstration, and he continued his research by offering important contributions to numerical computing.

Donovan explains how video games went through a series of false starts, at a time when pioneering studies on Artificial Intelligence and computer programming were expanding, because experimentation and advances 'remained steadfastly about research rather than entertainment (2010; 10). However, it was the very environment of academic computer research that finally paved the way for a game that would have far reaching consequences in inspiring the entrepreneurial spirit of figures like Nolan Bushnell that would introduce video games to the masses. The same type of excitement Higinbotham witnessed with

Tennis for Two arose once again a few years later at MIT through Steve Russell's *Spacewar!* Named in the wake of the space race, the game was developed on a DEC PDP-1 computer in 1961, and involved two players battling against each other by controlling a spaceship.

The controls and gameplay were more complex than Higinbotham's effort, with players able to control the speed and position of their vehicle and fire rockets at the opponent. The game was later expanded in 1962 by Russell's colleagues by adding a starfield map on the background, a central star that would have a gravitational pull towards the two spaceships and finally a warp function to transport the vehicles on a random location on the map. While still in its infancy, the development and fine-tuning of *Spacewar!* were the first examples of a coordinated team effort to design a video game and refine it with entertainment objectives in mind. While the game, as Donovan reminds, 'was imprisoned by the technology needed to run it' (2010; 12), and prohibitive costs prevented it to be commercialized, it became popular among MIT students and also spread to other colleges over ARPAnet. Among the enthusiasts playing *Spacewar!* was Nolan Bushnell, an engineering student at Utah University 'who loved video games, understood the amusement business, and had the charisma to sell his passion' (Bakie, 2011; 7). Inspired by Russell's creation, Bushnell designed *Computer Space,* overcoming the hardware costs by building a custom game-dedicated device, by most considered the first arcade machine. Entering in a partnership with Nutting Associates, an amusement company, Bushnell produced 1500 machines and demonstrated the game in 1971 in Chicago. Although the public's reception was poor, due to the complexity of the game and the difficult controls, Bushnell still saw the potential of the medium as a profitable business and went on to found his own company, ATARI Inc.. People were indeed attracted to video games, but were not yet ready to cope with the frustration of steep learning curves and trial and error gameplay. This feedback finally planted the seeds for ATARI's idea of *Pong*, developed in three months by "engineer" Al Alcorn, at a time when game designers also needed to build the entire hardware needed to run the software. In an interview in 2004, Bushnell recounts the 'several reasons that *Pong* was very successful'. 'It was extremely easy to play' he says, 'but very difficult to master' (GSN, 2004). The game featured two white paddles on each side of a black background hitting a bouncing ball whose velocity would gradually increase. Numbers to keep the score appeared on top of the screen, and sounds distinguished the bounces. Bushnell and Alcorn had captured what would be the fundamental components of the medium, drawing masses towards *Space Invaders* (Taito, 1978), *Pac-man* (Namco, 1980) or *Tetris* (Pajitnov, 1984), namely the interaction with the computer AI and the challenge based on a score/reward system. It is no surprise that decades after the appearance of the first popular games, and with the introduction of more sophisticated gameplay and interfaces and large 3D environments, these elements have become deeply ingrained in game design. Rouse (2001; 14), Bates (2004; 17-37) and Newman (2004; 16) indicate how interaction, challenge, control and immersion constitute some of the key factors sought by players. *Pong* was the archetype encapsulating the essence of the gaming experience. It also embodies the fundamental characteristics discussed earlier that define the medium of the video game.

While by today's standards, *Pong* may at first appear as a simple black and white rudimentary attempt at simulating table tennis featuring a minimalist design with few dots and lines on the screen, its popularity and warm welcome among the public at large during its first release ensured the official entry of video games in the mass entertainment market. It launched the rise of the arcades across America and marked the true beginnings of video game development. As Bakie indicates, 'ATARI struggled to keep up with orders for *Pong*, while other companies imitated it and exploited ATARI's success' (2011; 8). While not being the first of its kind, *Pong* initiates the history of video games in terms of their commercial success, and starts the industry making video games a global new medium. In 1972, *Pong* "tables" and arcade cabinets quickly spread across America and are soon adopted in Europe and Japan with equal success. From this moment onwards, video games gradually consolidate, alternating moments of uncertainty to key transitions that will shape the stable and creative industry that we know today and will have a significant impact on game design.

The proliferation of arcade cabinets heralding ATARI's *Pong* is soon paralleled by the birth of the first video game console in 1972, the Magnavox Odyessy designed by Ralph Baer. This represents the first transition of video game entertainment from public arcades to people's households. More than a transition, Baer had started developing his ideas as early as 1966, prior to the arcade video game explosion. As Baer explains, 'my vision was to do something novel and enjoyable with some of the forty million TV sets in the US' (2005; 14). Functioning by means of a game-dedicated computer machine connecting to a TV set, the Magnavox Odyssey came pre-loaded with twelve games and plastic overlays to attach to the screen to add different backgrounds. As Baer recounts, the Odyssey, whose development started in 1966, was a closed system and, like the early arcades, ran by means of a microchip with discrete logic, excluding the possibility of designing and adding new games for the machine. With a positive reception from the public and positive sales, Baer's device pioneered the first of the eight generations of video game home consoles that would eventually overtake the arcade industry.

A second significant moment for game design came with the possibility of adding new titles to the library of consoles and therefore launching games as a separated product, allowed by the integration of the first microprocessors that turned video-game consoles and the first home computers into programmable devices. In 1976 and 1977 the first programmable consoles are released, and video game design becomes a process independent from hardware design. Clones of major arcade hits were now being ported to home consoles, internal game design teams formed, and soon the idea of independent thirdparty developers arose, with Activision becoming the first studio in 1979 developing games for multiple consoles and arcades. The first moment of uncertainty comes, however, during this period, with most of the design focusing primarily on proposing home versions and alternative arcade clones of *Pong.* The poor quality of these clones and lack of innovation in game design cause the first industry crash (Donovan, 2010; Kent, 2001; Whittaker, 2004), due to a decreasing level of interest among the audience. As *Pong*'s era was clearly coming to an end, Toshido Nishikaido's *Space Invaders* (1978), after having caused enormous success in Japan (Ashcraft and Snow, 2008), arrives in America and Europe licensed by Midway. The game, inspired by ATARI's *Breakout* (1976) and H. G. Wells' *War of the Worlds*(1898), featured rows of aliens to be defeated by a laser cannon and, for the first time, a high score to beat. Nishikaido's creation reboots the game industry and paves the way for what many consider the first golden age of video games (Herz, 1997; Bakie, 2011; Donovan, 2010). During this period important innovations take place: more colourful graphics are introduced, as in *Pac-man* and simple plots and storylines are injected in the gameplay, as in Nintendo's *Donkey Kong* (1981). Vector graphics is also being experimented, as in *Star Wars* (Cinematronics, 1979), and ATARI's *Lunar Lander* (1979) and *Battlezone* (1980), replacing sprite-based 2D graphics with geometrical lines and patterns, thus setting the basis for future 3D development. Arcade games proliferate during the late 1970s and early 1980s, with the appearance of the first game characters coming from Japan, such as the aliens from *Space Invaders*, Donkey Kong, Jumpman (later becoming Mario) and his girlfriend (later becoming Princess Peach), and most notoriously Pac-man and the four ghosts known as Inky, Pinky, Blinky and Clyde.

Furthermore, it is also during this period that the first personal computers enter people's households. With the spread of Intel's first microprocessors able to run games, the 8080, used first in the arcade game *Gun Fight* (Bally, 1975), in 1977 the founders of Apple, Steve Jobs (previously working for ATARI) and Stephen Wozniak release the Apple II, the first personal programmable computer to become accessible to the general public. As Rehak reminds (2008; 78), the first types of software exploited were video games. He indicates how 'the Apple II was a gamer's dream, offering color graphics and sound capable of emulating the video games found in public arcades' (78). Aside from offering versions of popular coin-op games, the personal computer benefitted from a long tradition of text-based adventures designed by hobbyists and enthusiastic students on mainframe computers 'behind the closed doors of academia' (Donovan, 2010; 38). This represents a separate but nonetheless very important line of game design in which elements such as narrative-based adventures and fantasy worlds, puzzles, labyrinths, boss fights, locked doors and keys and treasure retrieval were first incorporated in the medium and would later converge with the console-based game design. Inspired by Weizenbaum's *ELIZA* (1966) experiment in Artificial Intelligence research, which involved text-based human-computer interaction by means of a language parser, early text-based adventures such as *Hunt the Wumpus* (Yob, 1972) allowed players to enter selected commands to move across rooms, caves and dungeons, perform actions and manipulate objects, receiving text-based hints and descriptions of events. In 1976, Crowther improved the concept by adding richer text descriptions of the fantasy worlds and allowing free input rather than discrete commands. The resulting game was known as *Adventure*, which benefitted from add-ons and improvements by other student, most notably Dan Woods at Stanford University and also inspired the design of *Zork* (1977-1979) by a group of MIT students that would later form the game adventure software house Infocom. Similarly, *Zork* cast players in the role of a nameless adventurer whose objective was to explore and navigate through a network of dungeons, face obstacles, solve puzzles and occasionally fight enemies, in order to retrieve hidden artifacts and treasures and finally find a way out of the labyrinth. The gameplay had no graphical representation and relied entirely on a language parser that provided descriptions of the environments and received input from the user in the form of directional commands (go north/south etc…), actions concerning the immediate environment and object manipulation. In the complete absence of any graphical rendering, key elements of the interaction between the user and the language parser were the perceived freedom of being able to type anything and move at will through the described sceneries, and the intelligent responses from a language parser able to recognize a large number of commands and also provide detailed descriptions of the locales in which players found themselves. Finally, a branched story-structure made decisions taken by the players in several situations during their virtual journey have an impact towards the direction and ending of the adventure.

Zork and *Adventure* not only sat the foundations for the adventure genre, which found its first graphical rendering with Roberta and Ken Williams' *Mystery House* (On-line Systems, 1980), but also injected the narrative element and story-driven concept in game design.

Jane Jensen, former game designer at Sierra On-Line, the game company founded by Roberta Williams, remembers how 'the adventure game genre developed around what the PC was capable of...exploration and storytelling' (GSN, 2004). Furthermore, they forged many gameplay and story elements of the RPG genre starting and pioneered the notion of persistent online game worlds from the first MUDs (Multi-User Domains) to today's MMORPGs (Massively-Multiplayer Online RPG). Personal computer and console/arcade game design will initially follow slightly separate lines of development, with PC titles benefitting from a more powerful architecture translating, especially in the early 1990s, into better graphics, larger game worlds such as *Myst* (Cyan, 1993), refining first person adventure and first person shooter genres, kickstarting the massive online RPGs, simulators, RTS (real-time strategy), offering a more prominent narrative content. Towards the end of the 1990s, however, with home consoles nearing the performance of average PCs, the development will converge and consolidate into the multi-platform game design of the present day.

Back in the early 1980s, however, the introduction of affordable personal computers outperforming the existing consoles had negative repercussions on the console/arcade industry, which faced another crisis in 1983. The leading console, ATARI 2600, disappointed players by releasing poor quality versions of popular arcades, while other console companies suffered heavy losses and discontinued the production of their device. Third-party developers had difficulties in selling their games and also started dismantling, and a general perception arose among consumers who 'began to believe that it was all a fad and lost confidence in the industry' (Bakie, 2011; 9). Two years later, in 1985, the final rebirth of video games occurred, tracing a long line of growth and development that has continued to the present time. The release of Nintendo's first console, the NES (Nintendo

Entertainment System), outside of Japan, Shigeru Miyamoto's creation of *Super Mario Bros.*, and Pajitnov's *Tetris* were the answer to breathe new life into the medium. From this moment onwards, major Japanese console makers such as Nintendo and Sega, and later Sony, will dominate the home gaming market, eventually leading to a decline of the arcade scene in the late 1990s. The console wars (Herz, 1997; 114) between the Japanese giants will prove fruitful for game design in general, with the birth and consolidation of many game genres, most notably platformers like *Super Mario Bros*., beat'em ups like *Street Fighter* (Capcom, 1987), action adventure RPGs like *The Legend of Zelda* (Nintendo,1986), side-scrollers and vertical shooters and racing/sports simulations. As Herz reminds, 'by the middle of the decade, distinct genres had evolved from archetypes like Asteroids, Space Invaders and Missile Commando into a whole menagerie of side-scrollers, maze games, driving games and martial arts contests' (1997; 24). With better colour 2D graphics and expanding technical boundaries, violent themes were depicted more realistically, generating concern and controversies. As Herz explains, acts such as shooting, killing and fighting had been part of game design since the early days. 'Violence was the obvious choice for a video game premise' she says, 'Put a target in front of the player and have him shoot in its general direction' (1997; 183). *Spacewar!* had this simple premise. Nevertheless, the increase of graphics realism led Midway's *Mortal Kombat* (1992) and Digital Pictures' interactive cinematic movie *Night Trap* (1992) to be targeted by US Senators Kohl and Lieberman as depicting excessive, realistic violence, and were subsequently banned.

However, as Herz notes, this 'only generated valuable publicity' (1997; 191) for such games, which returned on different platforms and led to the surfacing of imitations such as *Killer Instinct* (Rare, 1994) and whose themes of death and violence were being explored in titles like *Doom* (ID, 1993). Growing concerns led to the creation, in 1994, of a regulatory rating system, the ESRB (Entertainment Software Rating Board) which would categorize games according to their content and display the age rating on every title. While the controversy had negative repercussions on the medium, shifting the attention of the general public towards the effects of violent games on children, it also marked an important moment for video game design, as developers could now target specific audiences and enjoy more freedom in offering themes of a more mature nature.

The final major transition to affect game design and gaming experience in general occurred in the second part of the 1990s, with the adoption of real-time 3D graphics as the conventional visual mode of representation. Titles presenting the game world to the player through a three-dimensional perspective appeared as early as 1976, with ATARI's famous arcade *Night Driver*, which gave players the perception of first person driving through a dynamic night-time world. It was not, however, until the early 1990s that 3D graphics received a major boost thanks to titles being developed for PC platforms featuring superior technology. The game worlds had now become dynamic, allowing players to navigate them from a first-person perspective with environments and character models being rendered in three dimensions in real-time. Whether through the enemy-filled mazes of *Wolfenstein 3D* (ID, 1992), or the open, puzzle-filled environments of the *Myst* series, players were now given an extra dimension, depth, through which experience a novel sense of immersion. With the advent of the Playstation in 1994, designed specifically to benefit from 3D design, PC-related game genres and their distinctive elements of exploration and narrative finally converge with the console gaming market. First person shooters and adventures featuring extensive narrative and explorations like *Myst*'s sequel *Riven* (Cyan, 1997), *Medal of Honor* (Dreamworks, 1999) or *Half-life* (Valve, 2001) could now enjoy the multi-platform design that brings us directly to the contemporary era of video games.

The impact of real-time 3D graphics is summarized by Newman as 'a significant shift in the design, implementation and pleasure of videogames that arises from a lifting of technical constraints' (2004; 32). These technical constraints were primarily represented by the staticity of 2D game worlds, normally fixed by the boundaries of the screen, while the pleasures came with players' novel understanding of the spatiality of the game world, and a perceived freedom of the exploration act, now made seamless. The effect of the introduction of 3D design as a standard practice in game design does not only affect the visual representation, but also has important implications for the story content and the narrative structures used to deliver it. With the exception of text-based and graphical adventures and early Japanese RPGs such as *Final Fantasy* (Square, 1987), the story content of games, traditionally decorative, now becomes a potential cohesive element for the expanding game worlds, in need of more dedicated attention in the design process. The narrative structures, defined here as the techniques used to reveal the story content of the game, assume more recognizable connotations as do the narrative limits imposed by the medium.

1.3 Video game Narrative Structures

Before proceeding with the investigation and categorization of the narrative structures used in games, it may be useful to dedicate some attention to some important issues which highlight a gap between the academic research approaching games in terms of their narratives and game designers' increased interest in harnessing the storytelling potential of the platform. Later in this chapter a methodological divide will be discussed involving the narrativist and ludological approaches to the study of video games. While the narrativist current approaches games as texts applying methodologies employed in literary and film studies, the ludological current argues that the medium should be studied as a standalone discipline focusing on its rules and mechanics and considering any story/narrative content negligible. It will be shown how the very notion and possibility of narrative in games is being questioned, and how this depends on how flexible or narrow a narrative definition one is willing to embrace. To this regard, it is important to indicate that the theoretical approach in the present study underlying the analysis and categorization of game narrative structures and the consequent proposal of an AI model to generate a novel narrative structure does not result from an absolute alignment with either the narrativist or ludological position. On the contrary, it is only by incorporating fundamental elements belonging to both currents that it becomes possible to gain a clear understanding of the interplay between the narrative component and the other core elements constituting the basis of game design. More specificially, the present study starts with the assumption that, while games can function in the absence of a story and a narrative mechanism to narrate it, all games bear an intrinsic narrative potential. Whether or not this potential is harnessed may depend on factors such as designers' visions and intentions as well as the type of demands coming from the audience. However, even unexploited, this potential is intrinsic to the very nature of the medium and manifests itself at the most fundamental level of gameplay through the mimesis function. This function becomes apparent as soon as players start providing input to, and therefore participate in the fictional world depicted in the game and actively make decisions and perform actions which will have an impact on such world. The mimesis function can thus be considered as a natural extension of the alternative reality offered by video games and the alternative role adopted by the players. Through the mimesis mechanism, players assume a fictional role in a fictional world. Although the complexity of these elements may vary, the adoption of a persona is a most fundamental characteristic of video game interactivity and a core element to consider in game design. At the basis of this study lies the idea that the non-separable element of mimesis gives games the narrative potential which not only justifies, but indeed requires a narrativist focus in the ludologists' proposal of a standalone discipline of video game studies. Establishing the mimesis function as a core component determines the position of the current study as embracing the narrative potential of video games while simultaneously considering the medium worth investigating as a standalone discipline with apposite methodological tools rather than being incorporated into other pre-existing fields of inquiry.

Traditional objects of inquiry of narratology such as plot structures and the entities of narrator and narratee are identifiable in video games. *In The Logic of Narrative Possibilities* (1980), Bremond and Cancalon indicate how the study of narrative branches into the investigation of the narrating techniques and the laws governing the content being narrated. The applicability of this approach goes beyond a specific literary genre and indeed can embrace any scenario in which a series of events is being narrated, proving useful for the study of video games. While the video game narrating techniques categorized in this study will prove unique to the medium due to its interactivity so as to be defined through the novel and more suitable terminology of narrative architecture, the content matter present in video games can be approached and described through traditional narrative studies.

Barry (2002) describes how an influential branch of literary theory studies known as Structuralism, later transitioned into Post-Structuralism, including major figures in literary analysis such as Barthes, displayed an interest towards prose narratives 'as a complex of recurrent patterns or motifs' (49), trying to isolate a finite number of units of meaning, or 'lexies', which would then give rise to 'all possible actual narratives' (50). Most story-driven titles follow the circular model of narrative elaborated by Todorov in *The Poetics of Prose* (1977; 111):

> "An "ideal" narrative begins with a stable situation which is disturbed by some power or force. There results a state of disequilibrium; by the action of a force directed in the opposite direction, the equilibrium is re-established".

Indeed, the study of the constituents that make up a told story goes farther back than the Structuralist movement, with Russian Formalist Vladimir Propp and his study, in *Morphology of the Folk Tale* (1928), of the 31 fundamental narrative functions of folk tales, and further back to Aristotle's definitions in the eleventh and thirteenth chapters of his *Poetics* of Hamartia (fault), Anagnorisis (realization) and Peripeteia (reversal). In one of the earliest titles featuring a complete, albeit basic plot, like *Donkey Kong* it is possible to see how fundamental plot elements emerge. Donkey Kong kidnaps the princess, disrupting the order and requiring the hero, Jumpman, to overcome challenges to eventually rescue the princess and restore the initial order. Examples of plots following this circular pattern abound in game design. They also faithfully reflect Bremond and Cancalon's elementary narrative sequences (1980; 388) which give order and sense to the narrated matter and operate across the phases of virtualization (goal to be obtained), actualization (required actions to attain goal) and goal attained (act successful/mission completed). It is often the case in games that 'narration can alternate phases of amelioration and degradation according to a continuous cycle (Bremond&Cancalon, 1980; 390).

The disturbance of an orderly state is indeed fundamental to all games in giving players end and purpose to the objectives and challenges posed by the gameplay. The very presence of a challenge to provide motivation for play entails a prior presentation of the goal/objectives to achieve and an agent (the player) to carry out actions and making decisions in order to attain the goal. In traditional narrative operating across the degradation/amelioration cycles, according to Bremond and Cancalon (1980; 394), the narrator 'must make clear first the nature of the obstacle encountered, then the structures and measures taken to eliminate it'. Subsequently, the narrator will often describe the performance carried out by the agent to eliminate the obstacle and achieved specific goals. Translating this into game design, it is possible to see how all these elements are preserved – start of the level briefings and tutorials inform players on objectives, types of obstacles they will encounter and what actions they can take to succeed. However, the performance will not be described by a narrating entity, but will occur in real-time as the agent (player) progress through the level. During this process, the narrative architecture, operating through the AI, will trigger the occurring of events, replacing an explicit description. What in traditional narrative is considered as description of events linked by succession, in game design becomes real-time, direct unfolding of events. Not only, as Newman indicates, 'the premise of many video games is reminiscent of

Todorov's basic narrative structure' (2004; 91) but a closer comparison between Propp's seven dramatis personae (1928) and the typical characters present in storydriven video games will reveal how in the latter, especially in the RPG genre, these characters emerge regularly and their role has become conventional also in terms of the gameplay function they bear. Further notions regarding the function of narrative, the identity of narrator and narratee, and the temporality of the narrations also apply to games. According to Genette (1980), in no case is the narrator completely absent and every narrative implies a narrator and functions as the recounting of a series of events through different temporal dimensions. Events are narrated as they happen. Contrasts may arise with Genette's notion that all narratives are necessarily diegetic, and Prince's exclusion of real-time story representations from the realm of past-events narratives (1987), and are often used as arguments by the ludological current to deny the narrative dimension of video games.

However, when considering temporality of narration, Rimmon-Kenan distinguishes 'a type of narration which is simultaneous with the action' (2002; 93) which appears to be suitable for describing the type of narrative temporality employed in video games. Using the example of Butor's *La Modification*, Rimmon-Kennan explains how in this case the narrator, speaking through the story agent, 'seems to be verbalizing his actions while performing them' (2002; 93). This real-time narration comes very close to the way players experiences plot and events in video games, with the major difference being represented by the vehicle used to mediate the narration which in video games assumes the form of a direct visualization of the events triggered by players' actions.

This chapter considers the importance the narrative component has assumed in video game design and investigates the various forms it can take within the limits of the medium. Seeing games as narrative is possible by bearing in mind the following correspondences:

Narrator – Game designers

The game designer weaves the story and the order of its events into the fabric of the game world.

Narratee – Players/Spectators

The intended audience of every video game is principally the player.

Narration – Collaborative act between game designers and players

The game designer organizes the story content into the interactivity of the game. The unfolding of the events is triggered by the player's actions and progression.

Temporality – Simultaneous narration

The temporality of in-game narration translates into a real-time unfolding of the events. The story is told the very moment it occurs. This is fundamental for player's interactivity and agency within the game world.

The Notion of Narrative Architecture

While it is possible to draw correspondences between the fundamental elements upon which narratives are based and their counterpart in the medium of the video game, it is also important to consider how narrative operates in video games in a peculiar and unique way due to the medium's interactive nature and the active role required from the audience (in the form of providing continuous input). This leads to the more suitable concept of narrative architecture when investigating how stories are delivered in games. Narrative as architecture can therefore be envisioned as a semi-automated story-delivering system which is embedded inside the game world. More specifically, story elements waiting to be narrated/discovered are carefully placed inside the characters populating the game world and inside the scenery and structures constituting the level design, from buildings to furniture, chests, boxes and the whole range of environmental objects. Major events pertaining to the main story are also embedded in the game world and will similarly occur at specific checkpoints. The way in which the narrative architecture of a given game will deliver the story is dictated by how the player interacts with the game world. A crucial role in this process is played by the AI system, seen as a vehicle for triggering the delivery of chunks of the story by governing the behavior and responses of game elements during the interaction with the player/agent. This AI-guided system is a fundamental component of the narrative architecture in games in that it allows designers to greatly minimize the presence of an explicit narrating entity by replacing a direct narrating act with a real-time automated happening of in-game events determined by the player's interaction with the game world.

Finally, and perhaps more importantly, another fact needs to be acknowledged. The issues of whether games can be approached as narrative and what degree of importance should the storytelling aspect be given are of no concern to game designers. Presenting cohesive stories represents a strong drive in game design, observable since the mid-1990s.

During a recent interview, British game designer Dan Pinchbeck, author of the first person adventure and narrative-driven game *Dear Esther* and the horror-themed narrative adventure of *Amnesia: a Machine for Pigs* (The Chinese Room, 2013), expresses his excitement on the potential games have gained regarding storytelling. 'One of the really wonderful things about games in the last few years' he says, 'has been the huge advances in depth and detail in terms of storytelling, particularly using games to spin these extraordinary worlds' (2012). *Dear Esther* casts players on a seemingly uninhabited island on the Hebrides. There are no objectives to complete, no enemies to defeat, no puzzles to solve. The emphasis is placed on the free exploration of the eye-catching detailed and lonely environments during which an epistolary narrative is triggered and delivered through fragmented texts narrated by an unknown voice. Like Pinchbeck, many game designers nowadays approach the medium as a creative storytelling platform with the objective of delivering to players an engaging story experience where their choices and actions can determine the directions and outcomes of the story. When Yuki Ikeda speaks in his developer's diary (2013) of his upcoming project *Rain* (Acquire SCE Japan Studio, 2013), he emphasizes how the nature of the game is being built from the narrative premise of emotional contrasts of despair and curiosity faced by a child who gets lost in a desolate, rainy urban environment by following a girl. Similarly, other game designers, like Quantic Dream's David Cage, and Peter Molyneux, author of the *Fable* series (Lionhead Studios, 2004 - 2013), often speak of stories and player's agency in the events being narrated as the main inspiration governing their titles. Cage, for example, during an interview recounts how 'we wanted a better blend of storytelling and interactivity' (2012) as the main appeal for his most recent title *Heavy Rain* (2010), emphasizing the story-driven gameplay experience offered in the previous title *Fahrenheit* (2005). Players controlled different characters of the same story at different times, with a gameplay centered primarily on interactive dialogues and a multi-directional storyline leading to multiple endings.

While heavily story-centered titles like *Dear Esther* or *Heavy Rain* tend to be considered as alternative game experiences, with the majority of game titles retaining the traditional action and puzzle-solving elements, the story element has become a core component in the design process in general, often affecting the way the game world is built and the type of gameplay actions and interactive options which will be available to the player. Media scholar Henry Jenkins comments on how ‘while not all games tell stories, many do have narrative aspirations’ (2004; 119). Certainly game designers often embrace the possibility of exploiting the storytelling potential harnessing the computing power at their disposal, and ‘the elective affinity…between computer games and narrative frequently surfaces in the talk of designers’ (Ryan, 2006; 183). While the interest in narrative drastically increased with the advent of real-time 3D graphics, it safe to say that the storytelling component has been part of game design since the early days of the medium, though often kept to a minimum due to the hardware constraints of the technology of the time. Even games belonging to genres such as sports or driving simulations and whose premise is not based on recounting narrative events, still present the element of *mimesis* intrinsic to the nature of games and increasingly prominent in video games. As Ryan notes, a ‘unique achievement of computer games, compared to standard board games and sports, is to have integrated play within a narrative and fictional framework’ (2006; 182). In every video game, the player becomes what the player controls, assuming a role detached from reality and engaging in a leisure activity by performing actions in a fictional game world. The missing in-game story narrations and information regarding the identity of characters and/or fictional settings of early titles were nonetheless supplied externally through the instructions booklet to promote players’ immersion in the game. Salen and Zimmerman (2004; 371) use the example of ATARI’s *Super Breakout* (1978) to indicate the early tendency from game designers to create ‘backstories [to] position a player in the context of a larger story’. Thus, the act of destroying coloured bricks by means of a paddle becomes the encounter of a ‘one-man space shuttle’ with ‘one gigantic force field of some kind’ and the bouncing ball is players’ only weapon ‘to make it through the layers of this brightly coloured force field’. The tendency of embellishing the game experience with story elements and using these to appeal to players continued to represent a stable aspect of game marketing, first in the form of story information in booklets and game boxes to offer a fictional setting which could not otherwise be distinguished by playing the game due to graphical limitations. Ryan notes how ‘even in the 1980s, when computing power only allowed rudimentary graphics, developers promoted their products by promising a narrative experience that rivalled...action movies' (2006; 182). Over the last thirty-five years this has become a convention, with the function of introducing players to story settings that now find their full in-game realization, expanding beyond the synopsis on the paper.

The increased importance in the story component is also reflected by the adoption of themes and motifs by genres which traditionally minimized story elements. The *Need for Speed* (EA/Criterion, 1994-2014) driving simulation series regularly injects plot elements to car racing, while the puzzle game *Catherine* (ATLUS, 2012), builds a multi-branched story architecture around what is essentially a block-moving, logic puzzle-based gameplay. The game story, delivered through cinematic interludes and real-time interactive dialogues, is emphasized over the core gameplay since the beginning both through a long introductive sequence and on the box art:

> "Vincent Brooks has been struggling in his relationship with his girlfriend of five years, Katherine. He's fine with keeping things the way they are, but she's set her sights higher than that, and the word "marriage" has come up".

Many elements can testify for the rise of importance of narrative in game design. The expressive potential of games to bring to the screen fictional worlds of vast dimensions, populate them with large arrays of characters, and make them navigable has also attracted the attention of literature authors interested in harnessing the interactivity and dynamic expressiveness of the medium. Terry Pratchett's *Discworld Noir* (GT Interactive, 1999), Clive Barker's *Undying* (DreamWorks Interactive, 2001) and *Jericho* (Mercury Steam, 2007) to Sapkowski's *The Witcher* (CD Projeckt, 2007) and Glukhovsky's *Metro 2033* (4A Games, 2010) are notable examples of authors directly involved in the expansions of their world on the game medium.

After having established the importance of stories in video games, let us now direct the attention to what kind of narrative architectures are currently possible within the medium. Here four narrative structures are defined. They appear individually or combined in all games bearing any type of story content, regardless of its time of development or genre, and delineate the technical boundary of what is currently allowed by the medium.

1.3.1 *Pre-established narrative structure*

The pre-established type of narrative can be considered as the principal and most commonly used storytelling architecture used in titles offering any kind of story content. In its purest form, this type of structure offers designers a highly controlled story delivery environment governing the main plot of the game. Discussed by Juul as ‘narrative of progression’ (2005; 72-73), the story plot following this structure develops in a fixed, linear fashion that normally starts with an introductory sequence, in which the main fictional settings are presented along with the events that will disrupt the initial equilibrium. Their main function is to establish the identity of the game world and the role players will assume by introducing the protagonist or entity players will control, and provide narrative meaningfulness for the actions and interactions that will follow. The introduction can take a variety of forms and the amount of story information it will reveal can vary greatly. Opening sequences can be non-interactive, semi-interactive and fully interactive. In noninteractive introductions, players are passive spectators of cinematic cutscenes depicting the events that will set the theme of the game. For example, the opening sequence of Ninja Theory’s *Enslaved* (2010), inspired by the classic 16th century Chinese epic *Journey to the West*, represents a standard non-interactive introduction in which the main protagonists, in this case Monkey and the AI companion Trip, are shown as escaping a slave flying ship and crashing into a desolated, war-ravaged landscape guarded by mechanical entities. The presentation of the game world and the enemy agents is followed by a second sequence revealing the role players will assume and the reasons for their actions throughout the game. Trip places a headband on Monkey and explains how she will need his help and protection to travel to the West and reach her village.

Semi-interactive opening sequences are also frequent, with players often having a visual control of the world around them. In the first-person shooter *Bioshock*, the descent into the underwater city of Rapture occurs by means of a glass elevator through which players are free to direct their view towards the buildings, signs and commercials arising from the ocean floor. The opening of *Resident Evil 6* (Capcom, 2012), instead, puts players immediately in control of one of the protagonists. The introduction in this case serves as a tutorial mission in which combat and movement mechanics are explained through a fully interactive mission.

In the pre-established narrative, the pace and order through which the story will unfold are determined beforehand by the game designer, and will follow an unchanging path from start to end. The term pre-established refers to how bits of the story are revealed. As players “hit” certain checkpoints during the game, the next story sequence belonging to the primary plot is triggered. This normally coincides with the end of a mission and more generally upon reaching the end of a level. As can be observed in *Enslaved*, the initial sequence is followed by a linear gameplay requiring players to proceed from point A to point B in a straightforward path. Little or no freedom is given in terms of free exploration, with invisible walls physically blocking players from wandering beyond the pre-established mission path.

The linearity and narrowness of the gameplay closely follows those of the story, which is divided into fifteen logical chapters. In pre-established linear narratives, the game world unfolds in an orderly fashion along with the story. Levels or stages are presented as selfcontained units, often representing different locales and thematic blocks. Backtracking to previous levels or jumping to levels ahead normally is not possible, as each stage is dependent on the order with which the story unfolds. Linear structures are most typically employed in action-oriented series, especially highly cinematic first person shooters such as the series of *Call of Duty* (Infinity Ward/Treyarch, 2003-2013), *Battlefield* (DICE, 20022013) and *Killzone* (Guerrilla Games, 2004-2013), all characterized by intense gameplay sequences reminiscent of scripted cinematic set pieces, that will simply repeat if re-played or if restarted upon failing the missions.

Inter-level cutscenes or sequences act as spatial and temporal separators. While these normally establish the setting for the upcoming level, they can also recap on past events. As mentioned above, the inter-chapter interludes between levels in *Resident Evil: Revelations*, appearing in a TV series format, provide a synopsis of the previous events until the present time.

Once a level is completed a chunk of the story information is released by means of a cutscene until the final ending. Game designers can add more variety by dissecting the plot into several story branches and providing different endings according to key decisions players will take during the gameplay. Story-branching and multiple endings, however, do not affect the nature of the pre-established architecture, and simply position players onto parallel story railway paths. Finally, story elements as well as character development can take the form of in-game dialogues and texts, sometimes replacing the more common cutscene. In *Remember Me* (Dontnod, 2013), the story is released primarily through radio dialogues between Nilin, the main protagonist, and an unseen figure known as Edge. Occurring continuously during all missions, these dialogues, aside from informing players about the objectives, gradually reveal the true identity of the protagonist and the meaning of her actions. The order and pace of these intermittent narrative sequences, while minimizing what Newman indicates 'the segmentation of videogames into interactive and noninteractive sequences' (2004; 72), still occur according to the designer's intentions, and are beyond the player's control. In short, pre-established structures, which already guided the basic plots of early games like *Donkey Kong* or *Super Mario Bros.*, favour linear narratives which, while not excluding the existence of rich and complex plots, do not allow players to take a more direct control over the story. The nature, order and pace of story information are fixed and will incur into a repetitive patterns upon multiple playthroughs.

1.3.2 *Discovery narratives*

A higher degree of freedom in terms of pace and delivery of the story is true, however, of titles that implement a discovery narrative structure relying on players' free exploration of the game world and subsequent discovery of story information. In this case, the order with which the story events are narrated is not fixed, but can often vary according to how players decide to explore the game world and/or interact with other NPCs. More interaction with the characters encountered in the game can lead to more story elements being revealed, which Ryan refers to as 'microstories told by nonplaying characters' (2006; 201). RPGs like *Final Fantasy*, *Dragon Age: Origins* (BioWare, 2009) or *The Elder Scrolls V*: *Skyrim* (Bethesda Game Studios, 2011), heavily invest, for example, in large number of side-stories and side-quests that can be revealed only after players have met certain conditions, such as speaking to specific NPCs or exploring certain locations on the map. A pre-established, main story arc is still present, guiding the main events from the introduction to the ending sections across key event cutscenes. Its role, however, is of secondary importance, with the designer withdrawing large amounts of story information from the main narration in order to weave them into the game world and among its inhabitants. Both Ryan (2006; 201) and Jenkins refer to this structure as embedded narrative, which is ‘relatively unstructured and controlled by the player as they explore the game space and unlock its secrets’ (2004; 126).

The storytelling becomes, in this case, an act of narrative reconstruction and impacts on the overall understanding of the main plot. This can in fact be more or less complete according to how deeply players choose to explore the game world, the time spent across various sections on the map and how many scattered pieces of story information they are able to retrieve. A fertile ground for discovery narratives to be exploited is represented by the “open” game world. Games featuring open worlds are characterized by players being able to access large portions of the map without spatial or temporal restrictions, and explore them with no pre-established order. Open worlds offer a playground for paideia-oriented gameplay, offering players the possibility of stepping out of the main story plot and structured missions.

The latest *Tomb Raider* (Crystal Dynamics, 2012), for example, adopts the open world concept by giving players access to most areas of the Yamatai island in which the story takes place. The absence of level transitions permits players to freely wander around the island. Unhindered exploration of most locales on the map makes it possible to retrieve documents in the form of journals from previous inhabitants and lost artifacts which provide information regarding the curse engulfing the island, the identity of the people who were there before, and the meaning of the rituals of the secret Solarii cult of the Sun Queen. The main story plot, with Lara Croft rescuing a crew mate who was captured by the sect, unfolds through a number of set cutscenes and dialogues triggered after completing several missions whose instructions are available in the game menu and whose execution can be postponed indefinitely. Retrieval of journals and objects motivates players to explore the vast island and learn about its untold story also by encountering old ruins of World War II aircraft or ancient shrines of prayer.

Similarly, the *Assassin’s Creed* series also embraces the concept of open world, enabling players to experience unstructured gameplay sessions paralleling the main arc of events. This offers players the possibility to momentarily pause or step out of the main plot at any given time in order to navigate and explore cities, famous buildings, visit and interact with other characters and also discover parts of the story which are intentionally excluded of the main plot. Players are in control of the pace of the story, and are free to decide when to continue with the main plot, literally by carrying out main tasks and missions, and when to pause and dedicate some time to sightseeing and exploration. The size and accuracy of the cities, recreated in their entirety and with attention to historical authenticity and detail, represent ample opportunities and motivation for players to dedicate many hours of free roaming. The open-world of *Assassin's Creed* is designed to cast players in the midst of historical events occurring in the Holy Land at the time of the first crusades, in Italy during the Renaissance period, and, most recently, in America during the British colonization. It then becomes possible to visit (entering) for example, the poor district, Al-Aqsa Mosque or Solomon's Temple in Jerusalem, the port of Acre, the Great Mosque of Damascus, or to ride a gondola under Ponte dei Sospiri (Bridge of Sighs) in Venice, stroll along Ponte Vecchio in Florence, the Coliseum or Pantheon in Rome or even visit the Sistine Chapel in Vatican City to look at Michelangelo's newly painted frescoes. The world of *Assassin's Creed* is purposefully designed so that many secondary story elements emerge incidentally if players decide to head towards other locations external to the main story path. One main example can be mentioned which best describes this act of incidental discovery of additional story elements. Players travel across the port city of Jaffa, finding some sections of the place in ruins and shortly after having encountered Richard Lionheart who is heading with his army towards Jerusalem. A brief dialogue ensues where Richard provides information on the whereabouts of the next target to be assassinated, Robert de Sable, and no explanation is given about why Jaffa lies in ruins and why he is bringing his army to Jerusalem. To those players following the pre-established storyline and quickly advancing through the memory sequences, this may appear as a part left blank because not relevant to the main story. However, this information gap is filled if, during the first half of the game, players detach from the main story and freely roam the environments where they might chance upon a square in Damascus where an activist is speaking to a small crowd and, more specifically, cursing The Christian King (Richard) and praising the Saladin. If players linger around a little longer, they will hear the following message from the speaker:

"I stand before you to deliver a warning! Should Richard take Jaffa, there will be no stopping him! He will march on Jerusalem next. We must end this before it has a chance to begin".

Returning to Jaffa, the ruins are explained, as are Richard's motives for heading towards Jerusalem.

1.3.3 *Sandbox narrative*

The main story plot becomes even thinner and increasingly secondary with the third type of narrative, which can be defined as sandbox narrative. In this case, a more personalized series of events emerges as the result of players' interaction with the game world. This type of narrative is also identified by Ryan, who speaks of it as one 'that players write through their actions...within the range of possibilities offered by the built-in script' (2006; 201). Like discovery narrative, free interaction and exploration are at the core of sandbox games. However, the latter present a greater number of interactional possibilities distributed across the game world for players to engage with in order to remove the focus from the main story path and motivate players to engage in long sessions carrying out many activities in the fictional world. 'Give them a sandbox, and they will build castles' is, according to Breslin (2009), a recurrent motto among sandbox game developers, and translates in providing players with a vast open-ended world free from a pre-determined story path and filled with elements to interact with. Sandbox games like *Sleeping Dogs, Far Cry 3* (Ubisoft Montreal, 2012) or the Rockstar's *Grand Theft Auto* series (Rockstar North, 1997 - 2014) and *Red Dead Redemption,* are designed to maximize the paidia type of play and provide an interactive environment where players can exercise creativity and craft individual stories which maintain a sense of cohesiveness within the greater narrative framework. During the first sections of these games, which normally revolve around tutorial missions, instructions are offered about the interactive options players have while exploring the game world as a 'necessary framework guides the presentation of the sandbox elements as the world develops and unfolds' (Breslin, 2009).

While discovery narrative games like *Tomb Raider* or *Assassin's Creed* still keep certain areas inaccessible, free roaming sandbox games present fewer limitations in this case. As observed in *Red Dead Redemption,* the principal idea is to motivate players to spend a long time learning about the fictional world and its characters, and doing this in several ways. Upon entering one of the many saloons, for example, players can decide to verbally interact with the people inside while ordering a drink, sitting at a poker table, intervening in a quarrel or simply renting a room. Other locales offer different types of interactions, and the overall effect this system has in terms of narrative is a series of events and activities at the end of each gaming session which will differ from player to player.

In *Red Dead Redemption*, players' individual narratives are also promoted by a game world designed in such a way as to appear to have its own ecosystem with a number of built-in randomized systems. An accelerated day/night cycle is accompanied by a randomized weather system, which is developed so as to have a direct impact upon the morphology of the terrain, on the vegetation and animals populating the areas as well as the inhabitants of the various settlements scattered across the region. NPCs' behaviour is designed to respond logically to this type of environment. An NPC will therefore take shelter under a tree in the haze of a sunny day, but will run towards the nearest settlement and inside a saloon during heavy rainfall. Likewise, if NPCs are travelling during the night, chances are that they will set up a small camp and light a fire for warmth and to keep wild animals at bay. During wet and humid conditions, the terrain will become slippery and muddy, making it difficult for the protagonist and his horse and all other NPCs to travel across steep ridges and uncertain slopes. Likewise, accidental fires may spread across less arid sections of the map in case of long periods of draught. Events involving NPCs may also randomly occur throughout the game world, with players being able to intervene if they are in the immediate vicinity. If the body of an enemy, for example, is left unattended outside a settlement, vultures, wolves, hyenas and other animals may be attracted by the carcass. Similarly, solitary carriages travelling through isolated regions may face robbery, or riots and shootouts may occur after a game a poker in a saloon or discussions may ensue if a girl is being harassed. Aside from a number of unique events or encounters, which will happen only once, more random events, also known as "world events", will happen regularly throughout the game session, could generate at any point across the map with the right combination of variables, and the player can decide to intervene and settle the disputes or simply observe as a bystander. These random events, along with the several natural phenomena and states that can occur in the map at large are the result of AI techniques that rely on procedural content generation (PCG) and take advantage of algorithms that generate content automatically (Togelius et al., 2011). In Kushner's tutorial (2014), examples are given on how to enable the Unigine graphics engine to let the AI continue to build landscape features in real time. Finally, players can also encounter various behavioural responses from NPCs according to the reputation built through their actions. For example, reckless killing sprees or cheating at poker will create avoidance and players may no longer be given access to certain areas. On the other hand, providing help and support will result in NPCs trusting the player with certain requests and missions. This, along with the randomness and non-scripted nature of the time and location of the events occurring in *Red Dead Redemption*, contributes to promoting diversity of narrative events between gameplay sessions and between players. Players' feeling of creating their own story is, interestingly, reflected in their recording and editing their gaming sessions for upload on popular video channels such as YouTube as episodes of mini stories complete with title and plot.

1.3.4 *Computer-generated narrative*

The chance for players creating their own narratives is finally made possible by the fourth and last type of narrative structure allowed by the medium. This can be observed primarily in games belonging to the simulation genre, and can be distinguished from the other narrative structures by the absence of a main story plot and narrative setting. Simulation games provide players with virtual systems that simulate real-life settings, and 'afford considerable control and influence over the game world' (Newman 2004; 116). The generated narrative is represented by the combination of events resulting from players' choice of initial rules and conditions and setting of a large number of variables affecting the development of the simulated system. Will Wright's famous life simulation, *The Sims* (Maxis, 2000-2013), attempts to simulate daily activities of the life of a human family and require players to specify values governing the personality and characteristics of their Sims. Tools are given to customize their appearance and create from scratch their living environments. Players, for example, can build houses and gardens and decorate them with a very large selection of furniture and general items. After creating the initial environment and setting the internal variables for each Sim, players can either simply observe how these behave and live, or intervene and direct their actions. Players do not have direct control over the Sims, as these are meant to lead an autonomous virtual life through AI techniques in which behaviour trees are heavily implemented in order to make Sims more autonomous and therefore more entertaining to watch.

Each Sim will have a set of physical, mental and social desires to satisfy, and these can cover social interactions, family building and finding jobs, buying a larger house or simply spending time sleeping, watching TV or relaxing by a swimming pool in the garden. Sims will take action according to which need has to be satisfied and this will also depend upon their personality. The personality comes from the combination of traits and wishes, and can therefore have a large number of variations. The AI governs the Sims' decisions based on long-term wishes and random short-term objectives that are included in the satisfaction of mental or physical needs. The game world also provides constant information to the NPCs through the objects around them. Each object feeds information on how it will affect the Sims' mood and how it is to be used. This allows Sims to interact with their environment in interesting and varied ways without the player's intervention. For example, a Sim who needs to satisfy his or her "fun" need, and can choose between a pinball machine and a book. Since the personality will determine which object is used, a serious Sim will likely read a book while a playful one will opt for the pinball machine. These large amount of interconnected variables leads to the autonomous generation of various logically linked events that constitute self-contained narratives. Ryan points to 'retellability [as] a function of the particular nature of the generated events' (2006; 193). Not surprisingly, the variety of events occurring in *The Sims* often motivates players to record and uploaded their custom stories on popular internet channels, reflecting Wright's objective to provide users with 'a storytelling platform' (2012).

While *The Sims* undoubtedly lends itself well to the generation of logically connected events, all game simulations offering players control over the conditions and variables of the game world rather than controlling a particular agent, bear the same narrative potential.

While both Jenkins (2004) and Ryan (2006; 181-203), referring to Sales and Zimmerman's misleading explanation of emergence in video games (2004; 167) approach this type of narrative as "emergent", hinting to its supposedly non-programmed, unpredictable nature. This term is avoided in this context as emergent narrative would indicate a narrative that cannot be fully predicted, regardless of how many variable designers or players have knowledge of and is non-deterministic. Computer-generated narrative, instead, is specific to what we have observed in *The Sims*, in the form of diverse events generated through a combination of variables allowed by the game AI. The NPCs behaviour can be predicted with the knowledge of a quantity of values. A Sim will incur in the same patterns and behaviours if certain conditions repeat. On the contrary, an emergent system, as we will see in the next chapter, is non-deterministic, and within the same sets of values and conditions can give different behavioural responses. In the history of video game design, a very limited number of titles have employed non-deterministic AI techniques, namely *Creatures,* (Grand, 1996-2001) based on artificial neural network and genetic algorithm, and the creature entity in Molineux's *Black&White* series (Lionhead Studios, 2001-2005) leading to less predictable behaviour with the potential for emergent narratives. Simulation games, instead, will generate the same type of non-scripted narrative under the same conditions.

1.4 Academic Divide

'We all enter this field form *somewhere else*' states Aarseth (2001) during the "Year One" of game studies:

> "and the political and ideological baggage we bring from our old field inevitably determines and motivates our approaches. And even more importantly, do we stay or do we go back? Do we want a separate field named computer game studies, or do we want to claim the field for our old discipline? This is a common dilemma for any scholar in a new field".

In effect, in a later article in the first academic journal dedicated to the study of computer games, Aarseth aligns with the ludological desire for creating a line of inquiry on computer games based on a methodology built around the medium itself and its intrinsic rule-based features, minimizing the colonizing attempts from other disciplines, such as media, sociocultural and narratology studies.

While the intensity of the debate between ludology and narratology may have waned over the past few years due to the unwillingness and sometimes impossibility (except for some cases discussed below) of these to fuse together and also embrace other disciplines in one multi-faceted productive inquiry, the question of whether and how computer games tell stories can still ignite criticisms, dismissals and occasional debates.

In the recently established field of game studies (Aarseth, 2013), a general skepticism towards the capabilities of games to tell stories is clearly put forward by scholars basing their approach on ludology. Major proponents of a ludological approach partially or entirely free from narrativist influences are Markku Eskelinen (2001a, 2001b, 2004), Jesper Juul (1999, 2000, 2001), Espen Aarseth (2001, 2004) and Gonzalo Frasca (2003a, 2003b). According to Juul (2000), the lack of a theoretical understanding of computer games can be remedied only by adopting an approach rooted in ludology which would facilitate the forming of a theory of games suitable for the complex medium. This view excludes (and discards) the serious inquiry of any type of content, artistic, narrative, aesthetic, found in games and leads to the rejection of the communion between games and narrative which is perhaps best worded by Eskelinen, when he considers that ‘If I throw a ball at you, I don’t expect you to drop it and wait until it starts telling stories’ (2001). In this view, computer games are considered for what they are, namely games, engaging the players through the gameplay rules and mechanics. Juul defines games as a ‘pastime with formal and predefined set of rules for the progression of a game session, with built-in and quantitative definitions of success and failure’ (2000). He criticizes the holistic approach according to which ‘since we can tell stories about a game we have played, no genre or form can be *outside* of the narrative’ (2001).

For Eskelinen (2001; 6) trying to force an analysis of the narrative content of video games shifts the attention away from a study of the fundamental properties of video games. Referring to Murray’s attempt to read the ‘clear dramatic content’ behind the game of *Tetris*, seen as ‘an enactment of the overtasked lives of Americans in the 1990s’ (1997; 144), Eskelinen indicates how such an analysis does not teach us much about the game itself and applying an ‘interpretive violence’ (6) focusing on stories, seen as ‘uninteresting ornaments’ (8), is detrimental to the study of video games. Gonzalo Frasca also states that the narrative paradigm can ‘limit our understanding of the medium and our ability to create even more compelling games’ (2003b; 221). Frasca, while acknowledging the existence of shared features between narrative and games such as characters, settings and events, sees games functioning as simulations and narratives as representations. Simulations involve systems which can be manipulated and whose behavior and outcome will change according to the users' input, while narratives functions as descriptors of non-manipulative representations.

Relying on game historian David Parlett's strict definition of games (1999), as explained by Egenfeldt-Nielsen, Smith and Tosca (2013), as 'something that can be won, and by only one player or team' (37), ludologists consider computer games as primarily consisting of ends and means held together by rules and procedures. In Parlett's notion, achieving the objective before the opponent within a procedural rule framework defines the nature of a formal game (1999; 1). In the videoludic environment, the gaming experience for the player revolves around the manipulation of objects, equipment and environment and it is necessary to reach an end or objective. As ludologists argue, the player is involved in this manipulative experience in one single temporal scheme, whereas the narrative retelling of events involves the invention of 'one time scheme in terms of another time scheme' (Metz, 1974; 18). Whether games are seen as rule-based systems (Juul, 2005), simulations (Frasca, 2003) or cybernetic systems (Kucklich, 2002) the view is that the player's performance, actions and decisions in the game do not bear any narrative content, since this can be seen as a dramatic performance occurring in real time. As Juul indicates, 'you can't have narration and interactivity at the same time' (2001), reiterating his view that a game 'must not contain narration; everything must happen in the *now* of the playing' (2000). A major point of criticism among ludologists seems in fact to concern the player's ongoing interaction with the elements of the game world and the impossibility of narrating events, actions and interactions that have not taken place yet. Eskelinen (2001; 3) derives this temporal incompatibility from Prince's definitions of narrative (1987), in which live performance does not constitute narrative 'since these events, rather than being recounted, occur directly on stage' (58). The player does not, and cannot 'retell' in the form of a story events and actions that he/she is carrying out during the gameplay as these events are happening in real time. 'It is clear', indicates Juul, 'that the events represented cannot be *past* or *prior,* since we, as players, can influence them' (2001). He compares the acts of reading a novel or watching a movie, where in both cases the audience is aware that the events being narrated cannot be influenced and their beginning-end circle is already complete.

The second layer of temporality required for the recounting of linked events is not present, and it becomes potentially available only after the gameplay sessions have ended. Eskelinen

(2001; 3) adds that the apparent absence of narrator and narratee as viewed in Prince (1987) and Genette (1972) further separates the narrative possibility in games.

The strength of the ludological approach and its major contributions manifest themselves in the arguments showing that narration and gameplay or interactions are, in this case, separated entities. Aarseth (2004; 366) extends the idea of real-time participation in games to further detach narratives from games, comparing games to real life. Personal involvement and the ability to make choices and take decisions make games performative rather than descriptive acts.

Discussions about how the suitability of games to host narrative structures already arose during the mid-90s, constituting the start of what would become the narratology vs. ludology debate. Back in 1999, in his M.A. thesis 'A Clash between Game and Narrative', Juul discussed the differences between game interactivity and narrative which make the combination of the two components rather problematic. 'Computer games are not narratives', explains Juul:

> "Obviously many computer games do include narration or narrative elements in some form. But first of all, the narrative part is not what makes them computer games, rather the narrative tends be isolated from or even work against the computer-game-ness of the game." (1999)

Juul, also in line with Aarseth (1997; 124-125), goes on by mentioning the attempt at combining game and narrative in the example of Infocom's *Zork* series of text-based adventures, also known as Interactive Fiction. The series of *Zork* basically provides the user with an extremely simple interface in the form of a text on the screen. In order to progress, the narrative requires the user, who is the protagonist of the story, to make a number of decisions, mostly in the form of choosing which directions to navigate and the choice and method for manipulating objects by inputting simple text instructions through the game's text-parsing engine. According to Infocom designers (1984), the meaningfulness of the experience relies entirely on the user's power of imagination, with a clear avoidance of visual representations of the text and with a heavy focus on 'plot and characterization' rather than puzzle-solving sequences. The attempt is to provide users with a feeling 'akin to waking up inside a novel' (Infocom, 1984), where they are the protagonists of a well constructed plot in which they will make the decision and determine the conclusion. Yet, according to Juul, the promise of a truly interactive narrative experience remained just a promise, and did not materialize into the revolutionary interactive text experience it set out to be. This failure and the apparent fast decline of Interactive Fictions, was related to the very nature of the computer game as being essentially incompatible with a narrativefocused design. According to Juul and generally accepted among ludologists is the notion that players are interested not in the story, but in understanding the structure and mechanics of the game and how to obtain/improve the skills needed to progress, regardless of any plot which may or may not be there. Adding a significant story, according to Juul, would decrease the longevity of the game and its replayability, primarily due to the poor quality and clichéd nature of the storylines he could analyze at the time. In short, trying to experience the story in a game would ruin the gaming experience, since reading a novel and playing a game seemed to be two separate activities with little in common.

A middle position is, instead, adopted by media scholar Henry Jenkins, who has published extensively on video games from a wider perspective, exploring their cultural and political importance (1998b, 2006b), the gender divide (1998a), their educational potential (2003) and their relationships with other media in a the wider context of transmedia storytelling (2003a, 2006a). When approaching the relationship between games and narratives, he agrees with the need of preserving a discipline that 'respects the particularity of this emerging medium' as promised by ludology, but also points to the fact that games are 'spaces ripe with narrative possibilities' (2004; 119). As indicated above, the present study adopts a similar theoretical approach. It emphasizes the importance of a standalone field of inquiry towards games which recognizes the medium's unique features such as interactivity and AI and, at the same time, considers the element of mimesis as intrinsic to the medium. Through the element of mimesis video games become natural storytelling platforms which will consequently employ, with varying degrees of complexity, the four types of narrative architectures analyzed above.

Rather than investigating in detail the story content of video games, Jenkins, similarly to the present study, looks at the ways games could tell stories, namely the narrative architectures made possible by the medium. He describes environmental storytelling and evocative spaces, explaining how designers convey stories through the level design and by re-creating fictional worlds players have encountered in novels or movies before. Incidental narratives scattered through the environment and discoverable upon exploration are described, as are emergent stories of non-scripted simulation games.

Another wider approach positioning games in the phenomenon of transmedial storytelling described by Jenkins (2003a, 2007, 2011) is adopted by Margaret Mackey, as evident from her extensive study on several new digital media as storytelling vehicles and the interaction with the users in *Literacies Across Media* (2007). Her main interest revolves around new literacies, moving from classic children's stories of the 1880s through modern video games as she explores media and subject preferences and how we acquire information. She is interested in exploring the ways in which readers can interact with text through new forms of digital media such as CD/DVD Rom, interactive fictions, and a growing interest in computer games. In one of her latest works, *Narrative Pleasures in Young Adult Novels, Films and Video Game* (2011), Mackey carries out a qualitative study on the responses users/readers have when approaching narratives in books, movies and computer games. She approaches *Shadow of the Colossus* (Team Ico, 2005) from a narrative point of view, trying to understand, by interviewing and observing the subjects, the role that agency, interactivity and immersion play in the users' experiencing of the game story, and how this differs from the more traditional book and movie formats. In line with Jenkins, Murray and Ryan, she regards computer games as storytelling platforms offering readers a different type of experience and explains how elements related to video games, such as interfaces, gameplay mechanics and agency/interactivity, shape this experience. Rather than tailoring a methodology for approaching video games from the narrativist lens, she provides observations on how users experience the in-game story.

The crucial structural changes games have undergone with the establishment of 3D graphics, and the higher importance given to the story component in game design discussed early in this chapter has played a major role in spawning the interest for a narrative-oriented approach. Brenda Laurel, researcher of human-computer interaction, media scholar and game designer at ATARI, arguably provides the first important study on the implications the increasing complexity of interactions between users and computers and the relationship with the interface would have towards storytelling and story experiencing. Her text, *Computers* *as Theatre* (1991), in which Laurel applies, adapts and extends the literary theory of Aristotle's *Poetics* to form a new model of understanding for the interaction and communication between humans and computers, often referring to video games as a most promising stage for users to act in and create unique narrative universes, has largely inspired and perhaps initiated the narrativist approach towards the medium which will be established through the works from Janet Murray, Marie-Laure Ryan, Barry Atkins (2003) and Margaret Mackey. More specifically Laurel proposes the definition of video games and computer applications in general as platforms 'enabling humans to take actions in representational worlds' (1991; 19). She looks at the element of interactivity as a crucial design factor to facilitate the transition for the user into the fictional world. Variables such as how often interaction is possible –frequency-, how many options the user has available –range- and how much the users' actions matter in the fictional world –significance- contribute to make the user's participation in the virtual world relevant and engaging. Laurel continues by exploring how the combination of these interactive options with interfaces and graphical techniques that intensify a sensory first-person experience can augment the user's willing suspension of disbelief and the sense of immersion in representational realities. Although Laurel's analysis does not confine itself to games exclusively and embraces the entire realm of computer applications, seeing the computer as a theatrical stage for users to carry out actions that also matter in the real world, it is easy to see how her analysis serves as a solid foundation for observing how games can create fictional worlds and what role narratives can play in them.

Furthermore, the limited game technology of the time allowed Laurel only to make predictions and envision possibilities and, given the general nature of the study and its focus on interaction and agency rather than narrative, in-depth discussions on how stories and plots appeared in contemporary games are absent. Yet, her study comes at a crucial moment in game design, with vast navigable virtual game worlds appearing shortly after and leading designers to reconsider the importance of stories in their works and the ways, narratives, for delivering them.

Laurel's theoretical framework of computers as theatre re-emerges in the study of computer games as theatre and cyber-drama platforms in Janet Murray's *Hamlet on the Holodeck* (1997). Her background in literature studies and literary theory allows Murray to conduct an analysis of computer games focusing specifically on the narrative potential held by the medium and to provide some of the earliest examples of a narratological perspective applied to video games by discussing the storytelling features of some titles available at the time and what features need to be implemented in games in order to create the conditions for an immersive and different kind of narrative. Like Laurel, also Murray initially considers the possibility for computer applications in general to generate increasingly complex virtual environments and the beneficial implications for the users. During her literature tutoring activity in the 1980s at MIT, at the time one of the most fertile grounds for computer application development, Murray is able to observe how, aside from the more ordinary word counting and number processing applications, computers are being used by talented hackers to create fictional universes in the form of 'imaginary dungeons filled with trolls' (1997; 5). What she is witnessing is the development of the first MUDs, Multi-User Domains, arguably the first form of narrative-driven video games, in which users navigate maze-like environments displayed on the screen in the form of texts and have the ability to input a variety of commands to choose which direction to go and how to manipulate objects and key items described in the text in order to complete their quest. Inspired by Laurel's approach and by software programmer Papert that 'computers are tools for thinking and should be used to create microworlds (1997; 6), Murray sees games as most prominent computer applications for developing this concept and particularly for creating fictional worlds that can immerse users in a personal and unique narrative experience. From this perspective, video games can represent a new medium for storytelling and a new type of literature that makes use of features not available in other media. She brings forth the Holodeck example as the ultimate vision of what games could eventually achieve in terms of narrative, realistic details and immersion. The Holodeck is a technological wonder available in the Enterprise starship in the Star Trek TV series that enables passengers to enter a computer simulated world 'that looks and behaves like the actual world', with characters that 'can be touched, conversed with and even kissed' (15). The passengers engage in personalized fictional stories with plots that generate in a credible and natural way as a response to their actions and behaviors. It is a game designer's dream, a form of full Virtual Reality with a completely transparent interface allowing users to all type of interactions. Murray considers video games as harbingers of the Holodeck, and she points to four particular properties that differentiate them from other media and help them develop 'a narrative format of their own' (51). These four 'essential properties of digital environments'

(71) represent Murray's major contribution to the narrativist approach towards games and are defined as procedural, participatory, spatial and encyclopedic. The first two qualities are linked with the notion of interactivity in games, and more specifically how the computer responds to players' actions and what and how many interactions made users' participation in the virtual environment possible. The procedural property sees the computer as an engine, capable of producing 'complex, contingent behaviors' (72). This relates directly to the Artificial Intelligence, which in the case of games is deployed through the game-world and non-playable characters and how these are programmed to react and adapt to players' actions and decisions in a credible way. According to Murray, implementing the procedural aspect means to give users a greater illusion that the machine is actually listening to and responding to their input as though a human was on the other side instead of a computer.

This leads to the participatory aspect, another key feature in game design, which consists in virtual worlds and characters' capacity to respond to users' input. As an example, Murray analyzes the early text-based game *Zork*, and the several ways in which users interact with the fictional universe described in the text. Murray notes how different decisions lead to different narrative paths and outcomes. 'If you do not take the water with you', she comments, 'you will die of thirst. But if you drink the wrong water, you will be poisoned' (77). The narrative "branching" is further enhanced by a large number of internal rules regulating the objects found in the game, with each object responding in a different way according to the context in which it is being used and by a clever use of 'sarcastic templates' (77) to respond to users' inappropriate actions (i.e. "kill troll with newspaper" leading to "attacking a troll with newspaper is foolhardy").

The third feature Murray describes is the spatial element of digital environments. Game worlds represent navigable space for users to roam and explore at will. Unlike other media such as books and films, the navigation in the digital environments of games has no preestablished order, and Murray describes how in *Myst*, much of the game experience relies on the pleasure of exploring the detailed three-dimensional environments which also helps players uncover parts of the story. Navigating the digital game world becomes part of the story and 'the slamming of a dungeon door behind you is a moment of experiential drama that is only possible in a digital environment' (82). What Murray is pointing at is an effective way, which will continue to be refined and improved in game design especially after the introduction of three-dimensional graphics, to create narrative structures in which an integral part of the story is released by the environment as players explore vast gameworlds. Murray describes the final feature, ‘which holds the promise for the creation of narrative’ (83) as encyclopedic, namely the possibility for computers to pack enormous amounts of written, aural and visual data combined with their processing power. She approaches resource management game titles such as *SimCity* (Maxis, 1989) and *Sid Meier’s Civilization* (Microprose, 1991) as examples in which players build their own personal city or civilization and see how it develops according to the choices made and conditions set throughout the game. *SimCity* involves all the complexities of constructing a city, from terrain properties to underground grids and traffic control, while in *Civilization* players control the birth and development of an historical population from its origins in the prehistoric era until the present day through the intricacies of agriculture, religion, technological advancements and diplomacy. Given the large number of variables involved, the outcome can vary greatly from player to player, effectively leading to a personal type of narrative which is the result of the player’s unique interactions with the game system, and which leads Murray to identify the player as ‘interactor’ and therefore as ‘author’ (152) of a personal story.

While Laurel’s and Murray’s studies display a more general nature, and look to define the macro structure for games and computer applications to provide immersive digital environments and narratives, Marie-Laure Ryan’s approach looks specifically at how the definition of narrative can combine with the type of stories present in games, their suitability for a narrative-based inquiry and how features exclusive to games can combine with the narrative component. Inspired by Murray’s identification of specific properties unique to the video game medium, she explores what type of narratives can result from the properties of games and digital environments. However, her views about the future of narrative are diverging. In Murray’s vision, this culminates with a full sensory experience of the Holodeck. Ryan points to technological limitations relating to Artificial Intelligence not being complex enough to generate credible stories naturally tailored to users’ actions, emotions and behaviour. Furthermore, another crucial limit is imposed by the psychological implications of users becoming active agents of their story and experiencing real rather than simulated emotional responses, transforming the detached and pleasurable process of participating in other characters’ events and situations into an overwhelming and tragic first-person experience.

In Beyond Myth and Metaphor – The Case of Narrative in Digital Media (2000), Ryan first defines narrative as consisting of a signifier, identified as the discourse or act of storytelling, and a signified which represents the actual story content being narrated. She then describes the traditional constituents of narrative, represented by the setting, characters and events and the most common motive, problem solving, leading the characters to act in the setting. At the heart of Ryan's inquiry is how this basic narrative structure can combine with the feature of interactivity and its implications for the player's role as reader and coauthor. She defines interactivity as 'changing conditions determined by the user's input', and distinguishes four types of interactivity and how they 'open different possibilities on the level of narrative themes and plot configuration' (2000). The user's position as compared to the game world determines whether the interactivity is internal or external. The internal interactivity has players controlling a character within the game world, while in the so-called "God Games", players control the virtual world from an elevated, external position. They set up the general conditions for the world and characters to develop independently and can regularly intervene to change these conditions. The internal interactivity leads to the identification with a specific character/characters, while the external stance does not involve a 'concrete persona'. The second dichotomy is represented by the ontological/exploratory interactivity. While, according to Ryan, the exploratory interaction allows users to navigate the virtual world with no consequences for its settings and for the story, the ontological mode sees players taking decisions and carrying out actions which will alter the direction of the plot and will cause changes in the world itself.

It is clear, from Ryan's analysis, how the combination of these four interactive modes can impact the storytelling in the game and make players more or less active in the events being told. Ryan continues describing how different combinations lend themselves to different types of plots. Exploratory interactions are suitable for spatial narrative and narrative of place, where players discover and witness the story as they move around specific locations or travel across vast (virtual) distances. Mystery stories, instead, give users a more active role and task of solving puzzles so as to piece together events and story fragments. Ryan's application of interactivity to the different types of narrative is, however, limited. What transpires from her examples is the idea of players more as observers rather than co-authors. There are no examples of cases in which players can actually alter the course of the narrative, determine different endings or create a personalized story as the result of their unique interactions with the game world and characters. This is likely to be due to an incomplete awareness (as it is unfortunately often the case with game scholars) of the type of games available at the time of the study, some of which already provided innovative ways for players to have a more significant impact towards the story.

In 2006, however, Ryan returns to the methodological issues regarding the applicability of the narrative concept to video games, providing a structured response to the major arguments put forth by ludologists and establishing guidelines on what to investigate when looking at how games tell stories. In refuting the ludological criticism, she indicates how games can have internal figures of narrators, often in the form of voice-overs or pop-up messages confirming the actions players have carried out (185). In responding to Juul's comments on games missing narrative devices such as flashbacks, she considers the example of *Max Payne*, and how designers introduce a number of flash-back sequences recounting the protagonist's past and justifying his quest for vengeance. In responding to Eskelinen's statements (2001; 4) that narratives feature fixed order of events and are therefore incompatible with open-world or sandbox games where the order with which events unfold differ and micro-events unrelated to the main plot may take place, she indicates how 'well-designed games guarantee that each new situation will logically develop out of the preceding one' (186). The simultaneous happening of events in games is compared to 'narratives that do not look back at past events…the Grand Narratives of Religion, whose last events…are yet to happen', or the narratives of films and drama, which, through images, 'create the illusion of the immediate presence of their referent' (187). Finally, Ryan, similarly to Jenkins, lists a number of narrative architectures that should be investigated if adopting a narratological stance, from the pre-scripted plot to narratives of discovery, from NPCs' side-stories to stories created and re-told by players in sandbox games (201). Lacking in specific examples though it may be, Ryan's work serves as a good starting point to carry out more in-depth analyses and close readings of game titles.

Barry Atkins (2003) provides an important contribution in this regard, as he approaches games from the narrative point of view as "game fictions", providing in-depth investigations of particular titles. In *More than a Game* (2003), Atkins focuses his analysis specifically on video games, considering them a 'new type of text that required critical reading' (2). He realizes that the important objective of a narrativist approach to games is to investigate how stories are told and read in games rather than the content. He explains how the telling of stories works differently in video games, and is closely linked to gameplay mechanics, conventions and rules not available in novels and cinematography. For example, in the third-person adventure *Tomb Raider III* (Core Design, 1998), identified as a quest narrative, Atkins distinguishes two types of narrative. The first one is linear and preestablished, delivering bits of the story through cutscenes triggered after players reach the end of a level. The second type of narrative is, according to Atkins, 'something akin to a personal mini-movie…that is only produced as the result of player interaction' (37). In another title analyzed by Atkins, the first person science fiction adventure *Half Life*, there is no direct telling of the story through cutscenes and voice narrations. Mission briefings or text summaries informing players on what to do are absent. In this case, the plot and story information are rather delivered indirectly by the environment and through 'what is overheard' (57) or told to the silent protagonist. As Atkins puts it, 'should the audio speakers fail while we are playing *Half Life*, it is the absence of non-linguistic cues that might indicate the location and nature of a threat that would be the greatest loss to the game – not the loss of the words spoken by the game's other characters' (58). In the case of both games, the medium's unique mechanics lead to the creation of distinct narrative experiences. Atkins provides the first important analysis of the interaction between game design and storytelling, and although more narrative structures have consolidated since his study, the importance of his contribution lies applying the general concepts of interactive narratives explored by Laurel, Murray and Ryan directly to specific game titles.

Chapter 2. Deterministic Systems

2.1 Determinism: Problems and Implications for Video Game Design

"But I thought..."

"You thought?? What did you think?"

"I thought I was alive!"

"You're not supposed to think that sort of stuff, you're not supposed to think at all. Your behaviour is non-standard. Defective models have to be eliminated, that's my job. If a client comes back with complaints, I am going to have some explaining to do". *Kara* (Quantic Dream, 2012)

In Quantic Dream's short tech demo *Kara*, a dialogue takes place between a supervisor of an assembly line and the end product, an advanced general purpose synthetic agent named Kara. Accurately modelled after a human being, Kara is one item in a line of intelligent robots capable of speaking all languages, well-practiced in the arts of music and dance, and generally able to perform all types of tasks with the precision of computers. They are indeed computers designed to provide entertainment, companionship and housekeeping functions to prospective customers, and carry out all types of requests. Yet, Kara suddenly starts questioning her status as merchandise, and her "thinking" that she is alive, which in other contexts would represent perhaps mankind's greatest achievement of creating artificial sentient life, is seen by the tester not only as a flaw in the system, but as a potential deterrent for customers who may indeed be disappointed at Kara's bizarre behaviour.

This example effectively illustrates the current situation in artificial intelligence and game design, where the potential to push the boundaries of NPCs' behaviour towards nondeterministic directions is in contrast with the deterministic nature of video games and the conventional AI techniques employed providing NPC units and game worlds with largely, if not fully, predictable states, behaviours and responses.

In physics and mathematics, a deterministic system is one whose future states can be accurately predicted if its properties and initial conditions are known. In a deterministic system, the same input, or the same set of conditions, will generate the same output, or future state. Furthermore, the present and past states of a deterministic system are the result of the laws of causality; the initial conditions and inputs determine, therefore cause, the several states which, in turn, act as causes for future states in a chain reaction commonly exemplified by a falling row of dominoes. Factors such as randomness, probability and unpredictability are removed, whereas repetition and forecast are prominent, forming the scientific and philosophical view of determinism manifesting in one of its extreme, albeit erroneous, forms through Laplace's Demon:

> "Given for one instance an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it—an intelligence sufficiently vast to submit these data to analysis—it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes" (1902; 4).

While the possibility for a super-entity, or indeed, a super-computer to process all the information of our universe and trace it to its initial conditions has been deemed not possible due to the irreversibility of complex systems, the entropic principle of the second law of thermodynamics (Grazzini&Lucia, 1997; 605-609), Heisenberg's uncertainty principle in quantum mechanics (1927) and the impossibility of knowing with exact precision the initial conditions of the universe prior to the Planck Epoch when quantum fluctuations dominated, the knowledge of past, present and future of smaller and stable systems with known (as well as unknown) initial conditions is perfectly possible.

Our planetary system is one such example, a deterministic system in which, from the knowledge of its current or past configuration, it is possible, thanks to Newton's laws of universal gravitation, to infer with high precision the position and orbital trajectories of the planets, their moons and highly elliptical comets at any one time in the past or future during the solar system life cycle. It is therefore possible to calculate when Mars is at its farthest (401 million km) and nearest (54.6 million km) position relative to Earth to optimize a possible human mission, or the exact time when the next sun eclipse or comet passing will occur. Furthermore, by understanding the class of the Sun, its current state and its properties (mass, diameter, luminosity etc…), it is possible to predict its entire life cycle and its future transition into a red giant and consequently, the fate of the Earth.

Later in this chapter we will continue to explore further variations of deterministic systems closer to our daily life and their formal model represented by finite state machines. Also known as FSM, finite state machines are standard models for finite determinism: they consist of a finite number of states, and there is a pre-specified next state for every combination of current input and current state. By knowing the current and past states of a system, along with the rules of transition which depend on the type of input accepted, it is possible to predict the next state of a given system. FSMs are described in greater detail in due course. Nevertheless, it is already possible, through the mentioned examples, to understand some important implications which may appear problematic when turning our attention to video games. If a deterministic system, such as a video game, can be visualized in all its past, current and future states, and accurate predictions can therefore be made before the occurrence of future events, one may conclude that this detracts from the meaning and true impact of the decisions players make during gameplay. The sense of agency, which promotes among players the belief that their actions have a short-term and long-term impact upon the game world, simply becomes illusory. The nature and amount of events that can occur during gameplay are already established beforehand and made to match with the limited sets of actions and interactions given to players. For any action carried out by the player, there is normally one reaction only, and the outcome of every interaction is known and will keep on repeating itself under the same conditions. Many game titles, especially from the RPG and sandbox genres such as *Fable*, *Mass Effect*, *The Witcher* or Rockstar's *GTA* series, often promise players an experience where every one of their decision matters and has an impact on the game world and the story. For example, the art box of *Fable II* promises one such experience:

"Choose your path to glory and experience how those choices change you and the world forever. A new life, a unique adventure----every time!!!" (2008).

Likewise, prospective players of *Heavy Rain* are given this premise:
"Your smallest decisions can change everything. Play all four roles in this psychological thriller where every action you take has consequences. How this story unfolds is entirely up to you".

Flamboyant promises of this kind represent a common rhetoric in the video game industry and regularly emerge from designers' statements and during the advertising campaigns.

They reflect an attempt to capitalize on player's active role in the game and to intentionally boost the interactive possibilities with the game world beyond their deterministic and finite nature. However, since the choices given to players depend on the designers' intentions, rather than on players themselves, and the consequences are equally pre-established and contained within a close-ended system, the ludic experience eventually translates into a mise en scene, an act carefully crafted by the development studio to promote players' entertainment. Indeed, players are actors rather than agents, and the main problems with the interaction in a deterministic video game lie in the absence of free will and in the lack of responsibility for actions that have no genuine consequences, factors, as we will see, that have been at the core of the philosophical attempts to reconcile mankind's free will with a deterministic physical reality. According to Russel (2002), the problem of free will arising from a deterministic system with human as participants, whether in real life or in a virtual game world, is 'the well-known dilemma of determinism' (14). 'If an action was caused or necessitated', he explains, 'then it could not have been done freely, and hence the agent is not responsible for it' (14). In a video game environment, multiple decision choices are sometimes given to players to carry out a specific action or complete a certain mission. These, however, are limited and normally reflect reasonable choices humans would make in a similar context in real-life, with similarly modelled NPCs reactions. Yet, attempts to "think out of the box" and go beyond obvious choices and decisions do not lead to reactions in the game world other than those that are "supposed" to happen.

Kara, like NPCs and game world entities in video games, is a finite state machine possessing a discrete number of possible responses and behaviours initiated by external inputs coming from the user or the environment or pre-scripted sequences of autonomous states in the absence of such input. She is not "supposed" to display a kind of behaviour, in her case thinking that she is alive, that goes beyond the developer's initial design and control, as this would defy the very deterministic, or more precisely, pre-determined nature she is supposed to act according to. Likewise, non-playing characters in video games interact with the user and the game environment following pre-established sets of behaviours that trigger once certain conditions are fulfilled. Even in cases where stochastic elements are added to increase randomness of responses, the same inputs or conditions will inevitably produce a repetitive pattern of behaviours. When we look at what implications this may have for narrative in video games, we see how its reliance on the behaviour of the entities present in the game world (and therefore the events these may cause) makes it equally predictable and eventually repetitive and close-ended.

Indeed, in the previous chapter it has already been possible to observe how all the types of narrative structures made possible by the medium are essentially closed systems generating a number of outcomes which may vary in diversity and quantity but remains discrete and subject to accurate predictions. Even in simulations like *SimCity* or *The Sims*, where larger amounts of data and combinations of values are used to promote behavioural diversity among NPCs, the possible behavioural outcomes, and therefore narrative variants, are limited. They can be accurately predicted by knowing the initial properties given to a particular Sim and those of the surrounding objects and other Sims. In short, as will be explored in more detail later in this chapter, given the same scenario, the NPC will produce the same sets of actions and responses and make the same choices. This strictly deterministic nature of narrative structures does not only derives from intentional design choices, but cannot be otherwise as it is bound by the very nature of the medium and its prominently deterministic AI architecture.

This chapter presents a theoretical approach towards deterministic and nondeterministic systems. In order to understand the fundamental elements determining the nature of these systems, we look at specific examples of deterministic and nondeterministic systems in contemporary physics and analyze mathematical models providing a formal representation of the logic behind them. The objective is to understand how to escape determinism in video games in order to visualize nondeterministic game worlds and narrative structures. The notion of determinism is, in fact, central to this chapter, as its understanding is necessary in order to formulate a hypothesis on how to escape it and how to propose a nondeterministic model to be integrated into game design. Determinism is firstly addressed from a philosophical and scientific historical perspective, from the earliest speculations of the Greek atomists to the impact of Newtonian physics, its consolidation in classical physics and astronomy, and the final challenge posed by the quantum mechanics.

Immediately following the historical overview is an in-depth explanation of how to define a system along with descriptions and examples of deterministic and nondeterministic systems. In this section, the fundamental characteristics upon which the deterministic or nondeterministic nature of systems rest are identified and discussed, along with their repercussions on the elements of predictability, control and agency. Specific examples of observable deterministic systems in nature and as man-made devices are then taken under scrutiny for a better understanding of their formalized model, the Finite State Machine, which has ample application in video game AI, and its several variations from autonomous and non-autonomous, linear and nonlinear systems to the probabilistic models emerging from stochastic processes and Markovian chains. The general analysis of deterministic and nondeterministic systems serves as a theoretical discussion for the following chapters, in which the predominantly deterministic nature of video games is addressed after looking closely at the types of artificial intelligence techniques used in their design.

2.2 The History and Philosophy of Determinism/Non-determinism

It is safe to affirm that, even aside from philosophical and scientific investigations, the idea of determinism can be seen as a common response to sentient life's power of observation of the nature and the physical world. While quantum mechanics tells us that at the sub-atomic level reality is uncertain and probabilistic, at the macro level physical reality appears to be driven by regular patterns and cause-effect chains of events.

Whether events are considered to be the result of natural causes or supernatural intervention, their regularity of occurrence permits us to adapt our behaviour and make decisions accordingly. In human societies, the manner in which people live their life is generally based upon a deterministic view of the world, in the form of a reliance on the laws of causation. These, along with a simple observation of repeating events, enable us to predict the behaviour of objects and entities present in our surrounding environment and have a fair degree control over tools and devices of everyday use. In the animal world, a similar conclusion can be drawn when observing, for example, how predatory techniques often arise from an awareness of the prey animals' habitual behaviours and the properties of a given environment, with the latter also using the same environmental knowledge to escape predators. Indeed, many phenomena observed among living organisms, and the biological phenomena such as the Darwinian notions of adaptation and evolution observed on Earth appear to be shaped upon the deterministic rather than random aspects of the macro-world.

In the Western tradition, one of the earliest manifestations of an elaborated deterministic thought can be traced back to the pre-Socratic philosophers, with 'the Greek physiologoi or cosmologists' who were 'the first thinkers to look for causes in natural phenomena' (Doyle, 2011; 70). This is often in conjunction with the materialistic view of nature which was gaining momentum as early as the 6th century BC, through thinkers such as Thales, Anaximander, Anaxagoras and Empedocles (Bailey, 1964; 9-45), and was based upon an attempt to explain the world, its constituents and events through naturalistic causes rather than through interventions from supernatural forces and deities. The approach towards the understanding of the workings of nature becomes based upon reason and perception, with the ultimate objective of investigating the smallest, fundamental constituents of matter and discovering underlying natural laws governing the existence of everything. Heraclitus is one of the first figures to try to identify a unifying principle triggering the aggregation and transformation of all matter in the universe. He refers to the element of fire as the fundamental constituent of all matter in the universe and of the Lògos, the principle that gives coherence and unity to all natural changes and events in the world. Heraclitus' philosophy was based on the understanding of transformation/change as a universal force underlying all animate and inanimate entities in the form of constant, incessant movement.

According to Freeman, for Heraclitus 'nothing, not even the most stable-seeming and solid substance, is really at rest' (1946; 115). Everything, instead, is subject to a constant motion between opposites. In one of his fragments, Heraclitus refers to this change as 'Πόλεμος πάντων μὲν πατήρ ἐστι', an internal battle (Πόλεμος) seen as the father to all things, which is harmonized and governed by the Lògos, the underlying unity of all things. While the few fragments attributed to the philosopher do not reveal many details on the nature and workings of Lògos, they contribute to shed some light on its role as the principal natural cause determining and guiding all events in the universe. According to Heraclitus, 'this Lògos holds always' and 'all things come to be in accordance with this Lògos' (DK 22B1).

One logical implication of Heraclitus' thinking is that there are no external or arbitrary forces beyond the Logos such as chance, probability or divine intervention, and gaining an understanding of the working of the Lògos would enable us to explain the past, understand the present and predict the future. It is an early picture of the universe as being governed by natural and autonomous laws upon which neither chance nor human influence have any effects. It becomes the "necessity" formulated in the Atomist thinking, where a mechanistic determinism of nature is first explicitly proposed.

One of the first elaborations of determinism can be in fact attributed to Leucippus, the early founder of the Greek atomist doctrine adopted later by its most prominent figures of Democritus and Epicurus (Bailey, 1964; 64). Often mentioned in conjunction with Democritus, Leucippus is credited, according to Aristotle, with the first elaboration of the theory of Atoms (Freeman, 1946; 286), in line with the materialistic tradition and as a solution to the questions of 'Being and Not-Being, Becoming and Passing-Away, Change, Motion, and the validity of sense-perception' (1946; 286). He also adopts a similar vision to Heraclitus' Lògos, accepting the view of nature as being made of and driven by fundamental forces reducible to single entities. His attempt is to explain reality in all its transformations and events as a result of natural causes. Most of Leucippus' ideas come from the work associated with his name, *Megàs Diàkosmos* or *The Great World-Order*, whose only fragments appear in Hermann Diels' *Fragmenter der Vorsokratiker* (1903), which constituted the basis of the atomist thinking and which would later influence Democritus and Epicurus. Leucippus postulated the existence of atoms, an 'infinite number of bodies, and in constant motion, so small to be invisible' (Freeman, 1946; 86). Atoms, which according to Leucippus are the smallest and irreducible constituents of reality, freely move and collide in the empty space. He further explained how their aggregation, 'driven by a non-intelligent natural cause' (1946; 87), gives form to all matter in the universe, while their separation is but a transition to another aggregation of a different configuration. All matter in the observable reality is the result of different arrangements and combinations of atoms, which are the only permanent entity in the universe (Bailey, 1964; 78). In the atomist thinking the view emerges of a universe in which everything is the effect of natural laws governing the motion, aggregation and separation of atoms. In the first book of *Physics*, Aristotle speaks of, and interprets Leucippus' natural causes as chance governing the formation of all matter. While atoms move 'apparently at random and in all directions' (287), according to Leucippus 'nothing happens at random, all happens out of reason or by necessity' (289), indicating a prototypical deterministic view of nature in which nonspecified causal forces govern the motion and combination of atoms and therefore determine the origin, change and transformation of all matter in the physical reality with the consequence, as Doyle argues, of 'a world with but one possible future, completely determined by its past' (2011; 71). As noted in Bailey, Leucippus tried to 'exclude arbitrary and external forces' (1964; 85) in favour of natural laws driving the collisions and entanglements of atoms. Expanding on Leucippus' atomic theory with the notion of a universe infinite in time and space as a consequence of the assertion that nothing can be created out of nothing, Democritus is the first to propose a strong formulation of determinism, considered by Bailey as 'full and unhesitating' (1964; 121). What in fact, was for Leucippus a "necessity" governing the motions of atoms, assumes with Democritus the status of natural laws determining the past, present and future of all things in the universe and of the universe itself. Bailey (1964; 121) explains how Democritus also indicated how 'the whole course of things is foreordained from all eternity' and is the outcome of the 'original and eternal constitution' of the universe. All events are therefore seen as consequences of previous events and in turn determine future occurrences, with an inherent dependency on the starting conditions of the universe. The idea of a deterministic universe driven by laws of causality is also consistent with Democritus' attempts at explaining from a naturalistic perspective a wide range of observable phenomena. While the explanations themselves may at times appear naive and incorrect, the intention of identifying natural cause-effect links is a testimony of a deterministic thought that leaves no room for external forces and arbitrary or cause-less phenomena. These natural laws are represented by a cosmic whirl, which Democritus considers, as reported by Diogenes Laertius, as 'the cause of the creation of all things, the whirl which he calls necessity' (Hicks, 1972), in which atoms, following their motion, can fall and cluster together. The conditions under which specific atoms, which in Democritus' view can have different weight and dimension, fall together, cannot be detected and may appear to be led by chance because there is no design behind them, but are the result of natural processes.

With the materialist tradition and the atomist philosophers, a view emerges of a mechanistic universe driven by fundamental laws of nature governing the smallest, indivisible atoms or, in the case of Heraclitus, the unifying entity he called Logos. In the absence of an explicit discussion on man's role in the unfolding of the events in nature and on his ability to exert what Sorabji refers to as 'voluntariness of action' (1980; 243), one logical assumption is that human decisions, actions and destiny are evidently part of the machinery of nature and are determined, like other events, by the natural law of necessity.

The first response addressing the mechanistic view of the world and the concept of necessity put forward by Leucippus and Democritus behind every event comes from Aristotle, who, while not addressing the issue of free will in the unfolding of the events, introduces the notion of τστή or chance. In the fifth book of his *Metaphysics* (350 b.c.), he refers to chance as one type of causa sui event that is in itself capable of triggering chains of events but is not the result of a prior cause or specific event. The model proposed by Aristotle, consisting of essentially non-deterministic beginnings generating cause-effect chains of events can be seen as a prototypical form of the Soft Determinism model which, according to Foot (1957; 439) is widely accepted today. In this view, the non-deterministic uncertainty under which free will operates coexists with the deterministic and predictable nature of the macro world. In contrast with the strict deterministic view elaborated by the atomists, Aristotle disagreed with the notion of a single cause behind an event, believing instead in a simultaneous combination of multiple causes as being the origin of things. While seeing himself as continuing the causal investigation initiated by his predecessors and contemporaries, he pointed in his *Metaphysics* to a hitherto incomplete understanding of the types of causes, which he attempted to overcome by proposing material, formal, efficient and final causes or "aitia". Every entity and natural phenomenon could be explained as being the result of the combination and interplay of these four types of causes, which referred to the constituting matter (material), shape or status (form), the cause or force producing the change (efficient) and the purpose (final). If what determined all phenomena could be described by understanding the role of the four causes, chance and accidents also played an important role. For Aristotle, all sequences of events could be ultimately reduced to causeless originating events, known as "ἀρτῆ", or fresh starts, which could be either caused by chance, therefore random, or spontaneous. In the 6th book of *Metaphysics*, he indicates how, beyond the starting point of a cause-effect chain, there is nothing else, making the initial event 'fortuitous' (Book VI). Furthermore, as Doyle indicates, 'a break in the causal chain allowed us to feel our actions "depend on us"' (2011; 72). While Aristotle did not seem to confront and solve what will be later considered the hard problem of free will--- how to combine free action with chance and deterministic reality--- he seems to have considered humans and living creatures displaying complex behaviour as being outside the realms of chance and causal chains. In *Nichomachean Ethics*, Aristotle explains how the origins for our behaviour, when not caused by external factors, are to be found internally, depend on our will and are voluntary (III). When not coerced from external events, people are therefore responsible for their actions, as they are capable of making different decisions leading to different outcomes.

The basis for the debate over determinism vs. non-determinism and one of the major implications, free will, were thus already being set in the 4th century BC. Supernatural interventions had been excluded, and the view of a regular, causality driven universe which could be investigated through the way it manifested to human perception was being established. The gap that now needed to be closed regarded the role of man and his actions in the machinery of the universe and whether events could somehow be influenced instead of falling into the one-possible-future scenario. Following the steps of Leucippus and Democritus by embracing the atomistic thinking, but also accepting Aristotle's notion of accident and chance, Epicurus is among the first to directly address the causes of man's behaviour and the possibility of free will. Central to Epicurus' argument for free will and non-deterministic outcomes is the notion of "swerve", whereby atoms, while moving in the empty space, occasionally deviate from their pre-established path, 'thus initiating new causal chains' (Doyle, 2011; 72). According to Bailey, the 'swerve of the atoms is, no doubt...a breach of the fundamental laws of cause and effect', representing an unpredictable 'force for which no cause can be given' (1964; 320). While according to scholars (Bailey, 1964; Doyle, 2011) Epicurus does not speak of the swerve as the direct force responsible for man's free will, nor does he explains how free will actually takes place (Annas, 1992; 184) it is nevertheless during this nondeterministic "portal" created by the swerve of the atoms that both chance and free will become possible. In his *Letter to Menoeceus*, Epicurus indicates how 'necessity destroys responsibility and chance is inconstant; whereas our own actions are autonomous, and it is to them that praise and blame naturally attach' (133).

While the swerve appears to more directly represent Aristotle's random factor, τστή, man's freedom of choice is one of its most important benefits. For Epicurus, this was not only a 'very deliberate breach in the creed of necessity' (Bailey, 1964; 321), but his solution in finding a compromise between his materialistic and prominently deterministic approach to nature and his moral system based on the notions of good/pleasurable and evil/painful and their impact on man's life and his ultimate objective, key to the Epicureism, of reaching ataraxia or the tranquillity of the soul.

With the problem of free will now becoming more central in the early Hellenistic debate over the determinism of universe, and with the attempts from Aristotle and Epicurus to find an explanation for the coexistence of universal natural laws, chance and free will, the Stoic school of thought proposed a model which could presently be seen as the elegant solution known as compatibilism. Founded and developed by Zeno of Citium and Chrysippus, the Stoic school of philosophy 'solidified the idea of natural laws controlling all things, including the mind' (Doyle, 2011; 74). Their cosmology was based on the view of the universe as a single body located in empty space and constituted by an active and a passive principle (Bobzien, 1998; 17). The passive principle is undifferentiated mass, acted upon and given shape by the active principle, seen as the primitive cause, 'universal Reason' (Doyle, 2011; 74), which can be interpreted as the fundamental force/s of nature governing physical reality. According to Chrysippus, everything is the result of a rigid system of sequences of cause and effect, where the random element of Aristotle's chance is denied. The soft deterministic view presented by Aristotle and Epicurus is replaced by an unflinching chain of causal events extending from the very beginning and stretching far into the future through one-only possible states. Sharples explains how, in the Stoics' view,

'nothing could happen otherwise than it does, and in a given set of circumstances one and one only result can follow' (1983; 9). For Chrysippus, there are no spontaneous motions or events originating without a cause. The result from the throw of a die depends on the force that causes its motion, and the different, seemingly random outcomes after each throw are due to 'differences either in those causes [the force moving the die] or in the surroundings—even if we cannot detect them' (Bobzien, 1998; 39). Along with the inclusion of what today are accepted non-deterministic systems (complex, stochastic, markovian) into the strict determinism where only one possible future state is possible, Chrysippus also incorporated free will and freedom of action as a natural part (both passive and active) of the causal chains of events. Recurring in the Stoic thinking as well as in Aristotle and Epicurus is the notion that man's behaviour and actions are not necessitated by external factors only, but are also the result of his will, worded as 'ἐυ ἡμῖν'—that which depends on us, which gives people the power to choose between different decisions and courses of action and therefore affect the possible future outcomes.

The picture emerging from the early thinkers was that of a universe set in motion and determined by unchanging fundamental forces of nature and undergoing constant transformations through stable cause-effect chains. This predominantly deterministic machinery also contained a minor random and non-deterministic component with the power of breaking the causal chains of events and often related to or coinciding with man's freedom of action. This appeared as a viable solution to a world subject to the arbitrariness of deities. At the same time, the random component, Epicurus' swerve of the atoms offered a solution to the difficulties raised by Democritus' mechanistic atomism (Sharples, 2007; 4), liberating man from the slavery of a pre-determined fate and offering a way to preserve freedom and moral responsibility. Huby indicates how the random component was introduced 'as a solution to the problem of freewill' (1967; 353). The gods, if they exist, are oblivious of man and reality and do not intervene; the universe and the nature are governed by immutable laws; the past, present and future occur through causal chains, occasionally breached by chance, and human beings have the ability to generate actions by their own will, sometimes in contrast with the natural course of events, sometimes influencing the shape of future events. This view emerges from the Roman philosopher Lucretius, who adopts Epicurus' atomist model and embraces the swerve of the atoms as the direct cause for free will. In the second book of his *De Rerum Natura*, Lucretius elaborates the notion of *clinamen*, a slight inclination of the atoms which permits them to deviate from their primordial straightforward path and thus collide and cluster together to give origin to the early universe, life and man's free will. The non-deterministic nature of the *clinamen* appears in these verses:

"corpora cum deorsum rectum per inane feruntur,
ponderibus propiis, incerto tempore ferme incertisque
locis spatio depellere paulum" (II; 217-219).

The atoms (corpora), while travelling in the empty space downwards in a straight line (cum deorsum rectum per inane feruntur), spontaneously deviate, at an uncertain time (incerto tempore) and in uncertain places (incertis locis). According to Lucretius, they not only allow nature to create, but also allow people to generate decisions of their own will in their own mind in their search for wellbeing and pleasure. This random variable represented by the clinamen is a vital process to escape from the pre-determined fate (fati foedera rumpat) and ensure that cause does not follow cause since the beginning of time (ex infinito ne causam causa sequatur) in a strict, mechanistic manner.

It is possible to observe how, through the materialist and natural philosophers of the Greek and Roman period, nature can manifest itself as both deterministic and non-deterministic. The part of reality which is directly accessible to our senses is the result of identifiable causal chains and appears predictable. At the micro-scale, however, reality is made of indivisible particles whose motions and interactions escape the laws of causality, are subject to unpredictable changes and one of their consequences is free will. While this model was formed more than one thousand years before the scientific impact of Galileo, Newton and Quantum Mechanics on the view of the universe, it does not depart significantly from one of the most accepted models today by philosophers and scientist, known as adequate determinism.

2.3 Determinism/Non-determinism from Classical to Contemporary Physics

In the coming centuries during and after the decline of the Roman Empire, through the Middle Ages and the Modern period, once the prominently deterministic nature of the universe had been generally accepted, most of the attention was shifted towards the problem of free will. The study of the physical reality, its laws of nature and its predictability, became instead the domain of science, primarily with the spreading of the scientific method and the development of theories aiming at identifying universal laws and recurrent patterns in nature. Starting from Galileo, the investigation of nature took a significantly different direction from the previous methods of enquiry, becoming detached from philosophy and religion and adopting an a posteriori, empirical stance based on observation, hypothesis, experimentation, theory and mathematical models, laying the foundations for the scientific method and providing the tools to probe the deterministic nature of physical reality. Galileo saw the universe as a book standing open for everyone to see. Yet, to understand its secrets it is necessary to learn the language in which it is written, a language, according to Galileo, which is precise and able to convey the universal laws of nature:

> "questo grandissimo libro che continuamente ci sta aperto innanzi a gli occhi (io dico l'universo), ma non si puo intendere se prima non s'impara a intender la lingua, e conscer i caratteri, ne' quali è scritto. Egli è scritto in lingua matematica" (1623; VI - 232).[1]

The idea was gaining momentum of a universe whose logic could be understood by developing theories for the different phenomena and events which, given the same

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[1] ―This immense book which continuously stands open in front of our eyes (I mean the Universe), it cannot be understood unless the language and characters in which it is written are learned. It is written in the language of mathematics'.

circumstances, would hold true at different times and different locations and could be formalized through mathematics, the language of nature. This would reinforce not only the deterministic notion of reality, but also the search for and understanding of the causes underlying phenomena so that the same result for a specific event could be reproduced. During his teaching at the University of Pisa (Paschini, 1965; 70), Galileo further emphasized the importance of gathering empirical evidence to determine and explain the causes for specific events rather than merely holding faith, and this could be achieved only through a rigorous method of observations and testing of hypotheses. The widely accepted Aristotelian natural model was being questioned and, with many of its statements being refuted by empirical experimentation, would eventually be abandoned. Galileo's approach towards the study of nature not only revealed his acceptance of reality as governed by identifiable and recurring fundamental laws, but was indeed shaped after the notion of a deterministic, cause-effect driven universe. Through his methodology, Galileo indirectly proved that, if events were random or causeless, it would be impossible to reproduce them and achieve the same experimental results in different times and locations. For example, both his practical and thought experiments investigating the laws of bodies in free fall, Galileo proposed a theory explaining how bodies of different mass and composition would still fall at equal speed if travelling with minimal air resistance and particularly in the absence of any frictional force. Furthermore, he postulated that bodies of different mass would be subject to a constant acceleration not due to their weight, but to the gravitational force. His theories on falling bodies, especially those resulting from thought experiments (Galileo could not reproduce the same void of empty space) and exposed in his final work entitled *Discorsi e dimostrazioni matematiche intorno a due nuove scienze*, published in 1638, would eventually prove correct more than three centuries later, in 1971 on the Moon. During an extravehicular activity, the crew of Apollo 15 demonstrated Galileo's theory of free fall by dropping a feather and a hammer an observing how they touched the moon surface simultaneously in the absence of an atmosphere. His method, based on an objective reality whose phenomena can be investigated, explained and reproduced through hypotheses and verifiable theories, would represent the start of modern science and provide the tools to unveil the deterministic nature of the macro-reality.

While Galileo's thought experiments are also the first attempts to isolate the investigated phenomena from external noise and disturbing factors as in a laboratory, his method paved the way to understand behaviours of physical reality which could be reproduced and predicted. Reichenbach indicates how 'only with the development of the experimental method...could the remarkable idea that the variety of nature was a consequence of universal laws be in fact verified' (1978; 296). Shortly after Galileo, who introduced the basic principles for uncovering the deterministic nature of reality, Isaac Newton published his *Principia Mathematica* in 1687, laying the foundations of classical mechanics and physics and significantly reinforcing a strict deterministic vision of nature which would remain unquestioned until Einstein's General Theory of Relativity and the revolution of Quantum Mechanics. The three universal laws of motion and the law of universal gravitation presented in his *Principia* seemed to uncover the mechanistic nature of the universe by identifying precise laws governing all dynamical interactions between bodies on Earth and all planets and celestial bodies in the solar system. Their validity would prove true in all contexts and could be expressed in mathematical formula which would help predict nature's behaviour in certain phenomena with high precision. In the first book of Principia, as reported by Harper (2011), Newton indicates how 'it is enough that gravity should really exist, and should act according to the laws that we have set forth and should suffice for all the motions of the heavenly bodies and of our sea' (349). According to Newton's law of gravity, every object with mass in the universe attracts every other body with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. The force of gravity is the same on earth as it is between planets, and the tendency of objects to fall to the ground is the result of the gravitational attraction from the mass of our planet.

While Newton's theory, envisioning the force of gravity as propagating directly from the bodies in question, could not account for phenomena which would eventually be explained through Einstein's space-time curvature model, such as GPS signal delay due to a timespace distortion caused by the mass of the earth, it is still used to describe the dynamics of planets' revolution around the sun and of satellites relative to their planets. This would allow enough control and predictability over the several orbital states of the earth-moon system to ensure the success of the Apollo program. Furthermore, Newton's three laws of motion, describing how an object has the tendency to preserve its rest or motion state unless acted upon by a force, how alteration of motion is ever proportional to the motive force' and 'to every action there is always an equal and opposite reaction, provided a solid understanding over a wide range of phenomena and dynamics governing the interactions among moving bodies. Newton's physics not only contributed to the consolidation of the idea of nature as predictable and deterministic, but also provided the tools to accurately predict future states of natural phenomena and their interaction with man-made devices, for example automobiles and aircraft. While failing to account for phenomena close to the speed of light and for subatomic phenomena, in which gravity is negligible, Newton’s laws still hold their validity for a large number of phenomena of everyday life and provide a good approximation for planetary orbital behaviours.

Science was now developing around the idea of providing a firm grip over nature’s behaviour, allowing mankind to exercise a higher degree of control over it. This was only possible with a physical reality in which, at least at a level higher than the subatomic, the same conditions would always lead to the same result (past to present state), driven by causal laws expressed in mathematical formulas. Starting from Galileo, the vision of mathematics as the language to employ for understanding and control of nature was gaining momentum and, towards the end of the 17th century, the foundations for ordinary differential equations were being laid simultaneously by Gottfried Leibniz and Newton. Developed to describe the unknown functions of one or several variables of systems evolving over time and space, differential equations immediately became essential in calculating and predicting the several future states of a wide range of deterministic systems and phenomena. In the classical mechanics originating from Newton’s laws of motion, for example, differential equations could be used to describe the dynamics of moving bodies through the known values of position and velocity of an object and an arbitrary variable, in this case time. Stephen Hawking indicates how, following Newton’s contributions, the laws of nature appear to become quantitative and precise, promoting the idea of a universe which was completely deterministic (1988; 57). Laplace’s demon seemed now a theoretical possibility, as ‘physical determinism’, as Popper comments, ‘became the ruling faith among enlightened men’ (1979; 212) and helped spawn the industrial revolution. For a moment, nature seemed to appear naked and under the control of science, its laws and dynamics firmly established through mathematical equations. Along with Maxwell’s equations unifying electricity and magnetism, classical physics was leading to the realisation that ‘if everything in the universe was determined by strict physical laws then the future behaviour of any physical system...could be determined’ (Rae, 2004; 2).

Classical physics and scientific determinism remained unquestioned until the 20th century, when their universality was compromised by quantum mechanics and, later on, by the study of complex system. While still proving valid and sufficiently accurate when accounting for most of the macroscopic reality, the established laws of classical physics failed to account for the behaviours of sub-atomic particles and certain non-deterministic phenomena such as the seemingly spontaneous decay of radioactive atoms (Born, 1927; 9). Feynman indicates how, in trying to apply Newtonian physics to understand the motion of the electron around the nucleus, 'all kinds of predictions came out wrong' (1988; 5). With classical predictions disagreeing with experiments (Fayngold, 2013; 1). the studies and observations of the atom and its configuration led to the development, during the first half of the 20th century, of what is known today as Quantum Mechanics, initiated by the study of the properties of light and developed to explain the behaviour of the several families of elementary particles and the interactions of three of the four fundamental forces of nature--weak, strong and electromagnetic, governing them. Some of the major observations of the quantum world which broke the firm deterministic grasp of classical mechanics were represented by the phenomena of wave-particle duality, superposition, entanglement and the uncertainty principle. When observing the microscopic world of particles, human common perception was defied and the laws of classical physical, shaped after a deterministic macro-reality, were no longer applicable. These phenomena revealed the essentially probabilistic nature of reality at the sub-atomic levels, where exact measurements are simply not possible and predictions can never be fully accurate and rely on probability. Furthermore, the famous thought experiment of Shroedinger's cat indicated how quantum phenomena could be made to affect macroscopic systems. One of the fundamental principles of quantum physics is based on a probabilistic vision of reality. The uncertainty principle, elaborated by Heisenberg in 1927, tells us that it is not possible to know the position and momentum of the particle with exact precision simultaneously. If we determine the position of a particle, we can only guess its velocity and vice versa. This is in line with the wave-particle nature of elementary particles preventing us from assigning, as accepted in classical physics, simultaneous values to the position and momentum of a physical system being observed. Sir Arthur Eddington referred to this inherent uncertainty of nature at the smallest scales as Principle of Indeterminacy (1935; 97). He explained that 'what is lacking to secure a complete and certain prediction of the whole future is always *just half* of the total data that would be needed' (98). The better we know about the position of an electron, the lesser we know about its momentum. The uncertainty principle represents a fundamental concept in quantum mechanics and demonstrates an inescapable fact: that nature, at the smallest scale, is non-deterministic and cannot therefore be predicted with certainty. Eddington embraced this notion to herald his belief of nature as being inherently nondeterministic, and the inability to calculate position and velocity of a particle simultaneously is not due to hidden variables, but to an intrinsic characteristic of nature. The Copenhagen interpretation tells us that quantum mechanics cannot predict any outcomes with complete accuracy, and that all measurements, as indicated by Albert (1992; 79), are constrained by the uncertainty principle.

Other ideas developed in quantum mechanics would further distance science from the deterministic perception of reality. The concept of quantum superposition, for example, states that a particle can exist in all of its possible states simultaneously, and only upon measurement will it collapse into one specific configuration. The very act of measurement, which cannot be performed with the naked eye and requires instruments that will inevitably shine light upon the observed particles, creates an interference that prevents the understanding of all the properties and configurations of particles simultaneously. This is best expressed in the famous double-slit experiment which encapsulates the uncertainty and superposition phenomena. Feynman, in his *Lectures on Physics* (1964; 1-5), describes the experiment which consists of electrons being fired towards an end-screen having to pass through a double-slit obstacle placed half-way to the screen. The pattern left by the electrons on the screen is in line with their wave-like property, appearing as the result of an electron passing through both slits at the same time. As Feynman indicates, ‘the electrons arrive in lumps, like particles, and the probability of arrival of these lumps is distributed like the distribution of intensity of a wave’ (1-5). Nevertheless, placing a measurement instrument at the slits, and therefore performing an observation on whether the electron does indeed split and pass through both channels at once, causes the particle to fall into one specific state and position, passing only through one of the slits. Other phenomena such as quantum entanglement further defy not only the classical laws of physics and our common logic, but also the absolute speed limit at which information can travel in the universe, creating the phenomenon of non-locality. Einstein, Podolski and Rosen, acknowledged possibility that the ‘reality of [the quantities] *P* and *Q* depend upon the process of measurement carried out on the first system, which does not disturb the second system’ (1935; 780). However, they firmly maintained that ‘no reasonable definition of reality could be expected to permit this’

(780). The entanglement refers to two or more particles interacting in such a way that the configuration of one particle will instantly determine that of the other particle, or, as explained by Greene, ‘an instantaneous bond between what happens at widely separated locations’ (2005; 11), thus, according to Einstein, violating a fundamental principle of classical physics known as the principle of locality or ‘Prinzip der Nahewirkung’ (1948; 322).

A new picture of physical reality emerges where the certainty originating from Newtonian mechanics describing nature as predictable and deterministic only applies, with varying degrees of accuracy, to large-scale systems. At the microscopic level, instead, a nondeterministic world emerges dominated by a fundamental uncertainty that makes the prediction of future events (at the subatomic scale) a probabilistic process. On large scales, it is widely accepted that quantum uncertainty is negligible, and the future states of macrophenomena can still be predicted and approximated within acceptable limits. However, with the development of nonlinear dynamics studying complex systems, phenomena such as weather dynamics, population growth, economy, viral pandemics and emergent or generative systems such as Cellular Automata or indeed biological organisms, new layers of non-determinism are added to what once seemed to be the perfectly mechanistic clockwork of nature. To this regard, Hilborn indicates how, the deterministic link between cause and effect provided by differential equation ceases to function in nonlinear and chaotic systems, essentially making ‘the implementation of Laplace’s calculating Intelligence impossible’ (2000; 39). The appearance of the complex system of life on Earth, for example, is an emergent phenomenon hardly predictable, as is its spread and diversification across the types of species that lived on the planet. Driven by evolutionary laws, based on random gene mutations, and resulting from a high sensitivity towards the initial conditions and the continuous interaction with the environment, the life system, while manifesting itself at a macro level, cannot be predicted regarding its future states.

The balance between determinism, complexity and uncertainty makes the notion of adequate determinism as one to be accepted and in line with our current knowledge of the universe. This variation of the deterministic vision of nature holds that, while unpredictability and probability at the quantum level are accepted as true, their effect appears to be negligible at large scales and in everyday reality, where classical laws of physics are still the most accurate way to probe many, but not all, phenomena.

2.4 Contemporary Models of Deterministic and Nondeterministic Systems

Throughout the first part of this chapter, we have seen how the scientific view of physical reality has been subject to constant changes and reassessments, starting from the first philosophical investigations, through the scientific revolution and finally with the new understanding of reality proposed by quantum theory. In order to safeguard/preserve free will, and thus freedom/responsibility of action, the initially mechanistic view of nature led by immutable causation laws gradually allowed for an element of randomness where the power of deciding one's own actions regardless of previous events broke the deterministic causal chain. In essence, the non-deterministic notions such as those explored through the swerve of the atoms of Epicurus and the notion of clinamen elaborated by Lucretius permitted the existence of cause-less events, rendering man free from destiny and responsible for his decisions when not coerced by external circumstances. Still united through naturalistic philosophy, the issue of free will and determinism has eventually split into two separate domains with the advent of the scientific method, which led to a thorough, methodical and verifiable investigation of reality based on practical experimentation and gathering objective evidence. This not only challenged the early philosophical speculations about nature, often the results of pure observations and logical thinking, but destroyed what was then the widely accepted Aristotelian model of nature. Nature became the domain of science, with universal laws governing physical reality being discovered and yielding a new picture of the universe describable by mathematics and seemingly predictable in its phenomena.

The discussion of free will, now relegated to philosophy and psychological studies, has greatly depended on the type of picture of reality science was able to provide. We have approached the problem of determinism and free will from a bird's eye view, trying to understand what the implications are for the simulated reality of video games, and how these issues manifest themselves in a video game environment. Indeed, the major philosophical concern of combining a causality-driven reality with free will emerges, as pointed before, in a video game environment. In the current picture of reality, the determinism of macro-phenomena is paralleled by quantum probability and nondeterminism displayed by complex systems. It is specifically at these complex systems observed in nature and real-life that one must look in order to extrapolate the principles, suggested by nonlinear dynamics and Cellular Automata studies, to address the determinism in the narrative structures of video games and implement a model able to inject non-determinism into the AI architecture and lead to unpredictable outcomes.

Before looking specifically in the next chapter at how determinism manifests itself in video games through AI techniques controlling the behaviours of NPCs, and what its consequences are, it will be useful to understand the mechanics and structure of deterministic and nondeterministic systems, both natural and man-made. We then proceed to analyze the formal model, mentioned earlier, which describes a deterministic system, the finite state machine which, as shown later, represents an essential AI programming tool governing the behaviour of the game world and its units in their interactions with the player.

Principal questions we must ask are: a) what is a system, b) how can the states of deterministic and nondeterministic systems be predicted and c) what, if any, is the user's control over the system.

In their introduction to the study of chaos and complexity, Peak and Frame suggest how people live their everyday lives torn by what seem to be two contrasting expectations. 'Much of our everyday experience', they comment, 'is unexpected, apparently whimsical, seemingly beyond our control' (1994; 1). However, this unpredictability of events, resulting from the complexity of human life in its interaction with the environment, is paralleled by our taking for granted 'the long-term, reliable functioning of refrigerators, computers, and communication satellites' (1). It might be added that this sense of security provided by the deterministic structure of man-made devices is also increased by the same type of deterministic behaviour displayed by several physical systems in nature. According to Hilborn, a deterministic system can be considered as such if 'knowledge of the timeevolution equations, the parameters that describe the system and the initial conditions...in principle completely determine the subsequent behaviour of the system' (2000; 6). In short, if we know the state of a system have knowledge of its properties, parameters and initial conditions, we are able to predict what its next state will be. This can be said to be true for both autonomous systems behaving independently of any input, and non-autonomous systems changing their states on account of external influences or input.

2.4.1 *Systems*

In the preceding discussion of the history and development of determinism both in philosophy and science it appears logical that this particular view acquires meaning and validity only for as long as it results from observations of external bodies and entities.

Indeed, we have often encountered terms such as “the universe”, “nature”, “physical world” and “phenomena” as representing the most common framework against which philosophers and scientists developed and tested their ideas of determinism, non-determinism and uncertainty. We observe our surroundings, extract patterns and attempt to draw conclusions as to “how” things work, trying to identify laws and mechanics governing the physical world. During the observation process, we perceive our surroundings as being constituted by discrete entities and phenomena. We refer to these as systems, which can appear to be either in an interactive relationship or entirely separated from and non-influential to each other. It is only by looking at a system that we can extract behavioural patterns, study its various states and configurations and eventually decide whether or not its behaviour can be accurately predicted, whether it is a deterministic or nondeterministic system. Backlund (2000; 444), points to the fact that, although there may be many definitions of what a system is, these are not exclusive and ‘things which are not systems could be regarded as systems’. A system is commonly defined as a ‘set of entities with relations between them’ (Langefors, 1995; 55). These relations are represented by the interactions on various scales and levels of the units forming the system (Miller, 1995; 17, van Gigch, 1991; 30, Klir, 1991; 5). At the micro-scale atom nuclei, for example, can be considered as one the smallest physical discrete systems. Each nucleus represents a discrete spatial region containing an aggregate of protons and neutrons bound together by the strong force. The stability, and therefore the particular state of the nucleus is the result of the interaction between the strong force and the enormous repulsion among the densely packed positivelycharged protons. This example shows how the interactivity between the single constituents determines the state and behaviour of the system. In this case, the result of the interactivity between protons and the strong force leads to the stable state of the nucleus.

Conversely, on larger scales, and in the case of complex systems, it becomes more difficult to distinguish well defined spatial boundaries, especially regarding phenomena such as the weather, which result from a large number of complex interactions between elements separated in time and space. However, while there can be disagreements on whether or not a system must form an' integrated whole' and bear distinguishable functions (Skyttner, 1996; 35), or if it can be divided into independent sub-systems (Ackoff, 1981; 15), our analysis of deterministic and nondeterministic behaviour compels us to speak of systems in terms of their ability to display different sets of states and transitions between them through various types of interactions. This element provides a system with a capability to have properties which may change. The ability for a system to retain specific configurations under certain conditions and change configurations in the event of internal interactions and/or external stimuli is therefore a fundamental pre-requisite for the investigation of the nature of its dynamics. When we look at the subatomic system of the nucleus, for example, we can observe how its interacting parts (protons, neutrons and strong force) normally determine a stable state. This state can change by either external intervention, such as in the nuclear fission, or by an internal radioactive decay, also known as spontaneous fission, in the case of particular elements. The nucleus provides a useful representation of a system in which the interaction between its constituents determines its state and behaviour. Furthermore, this example is indicative of how systems can be internally made of a number of sub-systems and can themselves carry out interactive functions in larger systems.

In nature, the state of living organisms is the result of the functioning and interactions between internal organs, for example. Other examples may be observed in devices such as a personal computer, which is a system composed of a set of sub-components such as motherboard, CPU, GPU, RAM, storage devices and peripherals, each of which constitutes a discrete system in itself. To this regard, Von Bertalanffy (1973) speaks of hierarchical systems (28) and open systems (156). Systems can be part of a hierarchical architecture when each component or sub-system is part of a larger structure in a top-down fashion. Digital data storage devices represent common hierarchical systems in which single files and the hard disk represent respectively the bottom and top of a pyramid structure. According to internal and external input, each component is capable of affecting other components and the top system in its entirety. A corrupted file, for example, may determine the malfunctioning of the hard disk, preventing it from booting. Conversely, the malfunctioning of the hard disk due to hardware failure may lead to files and folder to become corrupted and inaccessible. Open systems, instead, are in constant interaction with other discrete systems, 'maintaining themselves in a continuous exchange of matter with the environment' (Von Bertalanffy, 1973; 156). For an open system to function properly, interactivity with the environment, and therefore with other systems, is necessary. Living organisms, for example, are open systems, requiring constant interaction with other environmental systems such as oxygen, temperature, nutrition or gravitational pull.

Planetary phenomena and systems such as the Earth's atmosphere, the motion of the oceans or volcanic activity are also open systems whose state and configuration are determined by the interaction of other elements present inside and outside of the Earth's environment. Finally, Backlund discusses the existence of closed systems, defining them as having 'no relation to any other system that is not a subsystem of it' (2000; 450). In a closed system there is no exchange of matter across the system's boundary, as for example in a tightly sealed jar. In the light of all the several types of systems discussed so far, central to all of them is their ability to display certain configurations at certain time intervals which can be regarded as states. Their transitions into different states are initiated by internal and external stimuli. All systems discussed, including closed systems, can be subject to change to their state according to external inputs. This dynamics is essential in our understanding and discussion of deterministic and nondeterministic systems.

2.4.2 *Deterministic systems*

By looking at phenomena in the physical world, several deterministic systems can be distinguished bearing the above mentioned properties of state-change predictability and dependency on parameters and initial conditions. The change of state of systems found in nature can be triggered by what Arthur Gill defines as 'excitation stimuli' (1962; 8-9), which will lead the system to produce an output in the form of transition to the next state. The excitation stimuli are represented by variables that can be a) internal, thus autonomously generated by the system itself, b) external or dependant on outside input, and c) intermediate, including a combination of internal and external input. By knowing the values of these variables it becomes possible to determine the system behaviour and the cycle of its state-changes. A phenomenon that can best exemplify the notion of a deterministic physical system is represented by the phase transition of thermodynamic systems. According to this phenomenon, elements found in nature can be subject to a transformation of states of matter (Anderson, 2005; 1) as specific external stimuli are applied. Berry and Smirnov define the particular state of a system as ‘a uniform distribution of particles in a region restricted by a boundary’ (2008; 7). When subject to external forces such as temperature or pressure, the energy of the system changes, triggering a rearrangement of the particles composing the system into a different configuration. In the case of water, the molecular H_2O aggregations change their configuration when changes of temperature are applied, leading the system to transition into three possible states: solid, liquid and gaseous. By knowing the current state of the system and its thermodynamical parameters, which in this case are dictated by external changes of temperature, we will be able to determine the behaviour of the system and the next state transition. Raising or diminishing the temperature will cause the system to reach the critical points of freezing, melting, evaporation and, in special circumstances, sublimation, with the water becoming ice, liquid or steam. Normally described by means of a phase diagram, the phase transition of water can be defined as a stable, non-autonomous deterministic system. In an unchanging environment, water will remain in its liquid, solid or gaseous form. Furthermore, it is also a linear system, as its response is proportional to the values of the external input. The time needed to cause the liquid → gaseous transition, for example, will be proportional to heat intensity. External heat transfer will rearrange the system in a predictable cycle, normally from solid to liquid to gaseous and vice versa. The less common sublimation phenomenon determining the state change from solid to gaseous, thus bypassing the intermediate liquid state, is also predictable in the presence of specific weather conditions.

Observing the deterministic nature of a phenomenon as common as water phase transition can provide useful insights into the fundamental mechanics of state transitions governing the behaviour of a large number of systems both present in nature and manufactured by man. The phase transition system represents a stable, non-autonomous deterministic system which remains immutable in the absence of external triggering factors. For example, in an environment with stable heat and pressure values, water will maintain its current state indefinitely.

Conversely, an autonomous deterministic system will change its state according to internal excitation stimuli, without the requirement for input coming from the outside. In nature it is possible to observe examples of autonomous systems particularly among living organisms, where the state changes defining the several life stages are triggered by internal autonomous mechanisms dictated by the genetic instructions coded in the DNA. Regardless of external conditions, and with the exception of gene malfunctioning or manipulation and extreme events leading to premature death, the ontogeny of a living organism will always develop across a pre-determined set of stages through a rigorous, predictable order. While differences between species and between individual members, along with environmental influence, leads to time variations for the onset of the stages, the order will strictly follow a general birth→adulthood→death cycle. An interesting example where the different life stages assume physical states remarkably different from each other is represented by those insect species whose ontogeny is subject to the phenomenon of holometabolism, or complete metamorphosis (Cranston & Gullan, 2005; 145). During the state changes of holometabolic insects, 'the body is largely reconstructed' (Cranston & Gullan, 2005; 151). The metamorphosis of some species, such as the Monarch Butterfly, will proceed through the following order:

a) <u>Embryonic</u>

b) <u>Larva</u>

c) <u>Pupa</u>

d) <u>Imago</u>

The embryonic development occurs once the egg is mature and has been deposited. The next stage follows the hatching of the egg and marks the period when the insect is in its larval state. At this stage, the internal variable which will trigger the next stage is 'a reduction in the amount of circulating juvenile hormone' (2005; 151), enabling the insect to enter the pupal period. In the pupal state the larva is enclosed in a protective shell or 'cuticle' (151), in which the body undergoes significant structural changes which will characterize the adult insect. Emergence from the cocoon, triggered by environmental 'changes in temperature or light' (152), marks the final stage of imago, or adulthood, characterized by sexual maturity and terminating once the sexual reproduction (for females) and mating (for males) has been carried out.

2.4.3 *Finite State Machines*

The phenomena of phase transition and holometabolism discussed above are examples of non-autonomous and (semi)-autonomous deterministic systems observable in nature. Their state transition depends on internal or external variables, as well as a combination of both. By knowing the state of the system at any one time, for example an insect in its pupal stage, it is possible to determine past and future states. Furthermore, knowledge of the values for the key variables such as the time when the state began and the environmental conditions, or, in the case of phase transitions, temperature and heat intensity, will allow for accurate predictions on when the next state will occur. These examples observed in nature can be seen as the real life counterpart of deterministic models found in systems and devices of everyday use, such as computers, communication devices, household utilities, vehicles, hospital equipment and generally a wide range of applications people and societies rely on. Indeed, these machines are logical systems whose design criteria are based on the ideas of determinism, predictability and control observed in natural systems. In addition to physical objects and machinery, autonomous and non-autonomous finite systems are widely employed in the field of Artificial Intelligence. They are used to govern the behaviour of synthetic agents deployed in the real physical environment, for example unmanned exploratory rovers sent to Mars to perform various scientific experiments and operate independently when remote control from Earth is not available.

Finite State Machines are also extensively used to determine the behaviour of entities in a virtual environment and principally in video games. Every non-playable entity in a video game represents a system with a finite number of possible states. The transition to different states will depend, as observed in the natural examples discussed above, on external inputs (from the player or from other NPCs), or will be determined by an autonomous state change cycle established beforehand and upon which player’s input will have no effect. Finally, many FSM models, especially those found software and hardware-based Artificial Intelligence agent applications, are driven by a ‘hybrid model’ combining ‘time-driven dynamics with event-driven dynamics’ (Cassandras&Lafortune, 2007; 269). A time-driven dynamics refers to systems changing state according to internal time-values, while eventdriven systems will require the occurrence of external events.

One example of a hybrid model comes from one of the latest exploratory rovers sent on the planet Mars, Curiosity, which is equipped with an internal FSM-modelled Artificial Intelligence. This provides the rover with an autonomous succession of state changes when not being remotely controlled from Earth. The rover may be autonomously exploring a designated area feeding sets of data back to Earth at regular intervals, with the cycle repeating itself until a specific event occurs. This event may be the presence of a specific rock entering the machine's line of sight, which will interrupt the rover's current state and activate a new sample-collecting state, whether by the machine's autonomous decision making system or by external input from Earth. Similarly, the machine is equipped by an autonomous navigational system which will maintain the same state until some terrain obstacles are encountered, activating a range of object-avoidance states based on the nature of the obstacle.

Synthetic agents modelled according to the FSM model architecture bear the same logical and controllable nature of physical digital and mechanical devices and ultimately represent formal and isolated (noise-free) models of similar systems observable in nature. The input water requires in order to reach its boiling or freezing point and therefore producing ice or steam as output follows the same logic of an in-game enemy NPCs to transition into alert or attack mode. Similarly, an ordinary input-output physical system such as an ATM machine will require external input such as the insertion of a debit card, and will produce specific outputs (cash, bank statements etc…) according to the user's type of input. In the absence of external input, an ATM machine will revert to its default state and in some instances it may run a "demo" mode consisting of cyclic pre-programmed outputs (i.e. operation instructions or bank commercials).

Cassandras and Lafortune indicate how 'a vast body of mathematical tools and techniques has been developed to model, analyze and control the systems around us' (2007; 1). In order to understand, analyze and reproduce the behaviour of deterministic systems, a formal model has been developed in the form of Finite State Machines. In elaborating one of the first formulations for the Finite State Machine theory, Arthur Gill defines such system as consisting of a 'finite input alphabet *X*, …a finite output alphabet *Z*, [and] a finite state set *S*'

(1962; 7). Such system will only accept a finite number of possible inputs and will respond through a finite number of possible outputs which will determine the next state of the machine. Two important characteristics of the FSM model are represented by its time discreteness and its deterministic nature. The values associated with external inputs and system outputs (excitation and response variables) are measured only at ‘discrete instants of time’ (Gill, 1962; 2), and all the variables determining the system’s behaviour ‘are not subject to any uncertainty’ (8). Directly inspired by natural phenomena and ‘the earliest considerations of physical matter’ (Wright, 2005; 1), the Finite State Machine identifies the state of a system at any specific point in time and looks at the possible states a system can assume, the behaviour and properties of each of the states and how transitions between states can occur. The Finite State Machine model allows us to abstract and isolate the rules governing natural systems and harness them for the design of devices based on logical architectures. According to Cassandras and Lafortune, one of the major functions of such a model is that of being able to duplicate ‘the behaviour of the system itself’ (2007; 2). In the fields of computation and AI FSM models are widely used and represent an essential reference to design the behaviour of synthetic agents with varying degrees of diversity and complexity. Furthermore, event-driven systems with input/output mechanics rest on the fundamental idea of user interaction which is arguably one of the most important features of the video game medium.

Rockstar’s AI programmer Alex Champandard indicates how Finite State Machines are essential to craft synthetic agents’ behaviour due to their efficiency in generating logically sequential models and determining the agents’ ‘current task and how they need to react to the situation’ (2004; 509). An FSM model consists of a set number of states controlled by transition rules and will possess an initial or default state. The transition rules specify the types of input or events needed to activate the transition from one state to another and therefore cause the system to produce an output. The output will depend upon the combination of the system’s current state and the type of input received. A basic FSM model can be represented by a light switch, and will appear as follows:

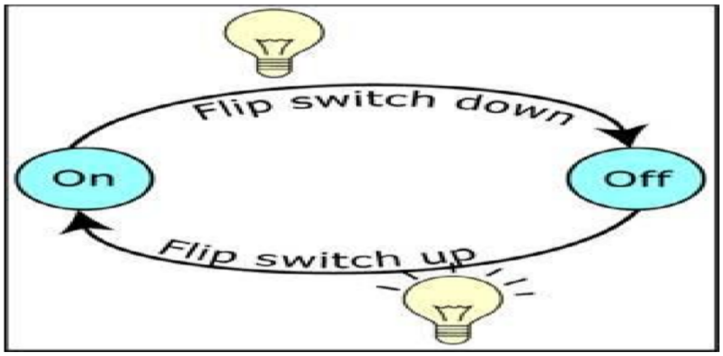


Figure 1. Example of FSM architecture of a light bulb switch.

The system, in this case represented by the light bulb, can assume two possible states: on or off. The transition rules are identified with two possible input actions, namely the switch being flipped up or down. The next state of the system will therefore depend on its current state and the type of input. If the light is off, input received in the form of moving up the switch will trigger the "on" state. Likewise, the opposite input will return the system to its "off" state. This very basic example serves to illustrate the fundamental logic governing Finite State Machines and according to which many physical as well as virtual systems are designed. In a slightly more complex example, Wright considers the model for a mechanical soda dispensing machine (2005; 2-6) consisting of a "coin return" button and a "drink release" button. There are three types of available inputs: insert coins, release drink, return coins. The machine will have three possible states or outputs: rest state (waiting for right amount of coins), ready to deliver drink, ready to return change. Inserting the correct amount will change the state from rest to ready to deliver drink. At this point the user can press either the drink release button or the coin return button, determining the machine's next state. Inputs will lead to the desired output only if performed in the correct order, and will otherwise result in a "null" output, for example pressing the drink release or coin return buttons without inserting coins. In a Finite State Machine model each state can accept specific inputs and refuse invalid ones. Whether or not a specific input recognized as valid is determined by acceptors, namely sequence detectors that provide a yes/no answer in binary 1/0 form.

The examples observed so far represent basic FSM models, but it is easy to imagine how additional layers of states and possible inputs can be introduced according to the functions and desired outputs of a given device, thus increasing the complexity of the system's behaviour. As we will see in more detail in game AI programming, FSMs are implemented primarily synthetic agents' lower-level functions, namely their behaviour when reacting to the immediate surroundings or in proximity of particular objects/events, and will often consist of algorithmic strings such as:

```
If (state)
 If (TargetInRange 3.0)
    x
If (TargetInRange 5.0)
    y
If (TargetInRange 7.0)
    z
```

According to Charles et al. (2008; 7) Finite State Machines are 'core components in the game-developers AI toolbox' used to 'have game characters switch between different preprogrammed behaviours'. Being often referred to as simply "scripts" (Champandard, 2004; 9), they represent the conventional method for crafting unit behaviour in a predictable and controllable game environment.

2.4.4 *Stochastic and Markovian Nondeterministic Systems*

So far we have observed a number of examples of deterministic systems and how their behaviour and state transitions can be predicted by knowing the current and past states of the system and by understanding the types of stimuli it is sensitive too. If the phase transition of water responds to external stimuli such as temperature and pressure, the holometabolic processes found in insects follow internal DNA instructions. The same deterministic mechanics applies to a large number of man-made devices designed around input/output architectures and which rely on user's interactivity for their functioning. The formal model encapsulating the nature of deterministic systems and devices is the Finite State Machine, which bears a finite number of possible states (outputs) triggered by a finite number of input options.

There are, however, systems which, while carrying the similar properties of maintaining a state at a specific time interval and transitioning into different states through input, bear an intrinsic uncertainty or randomness in terms of what their next state will be, making it possible only to guess or approximate any predictions. These systems can be described as being nondeterministic. Norris (1998) explains, for example, how Markov Chains can be regarded as nondeterministic systems whose next state is only partially known. First formalized by Russian mathematician Andrey Markov, systems of this nature possess a finite number of discrete states or steps whose sequence predictability is stochastic instead of certain. An essential difference with deterministic systems, therefore, lies in the state transition being "memoryless", as 'it retains no memory of where it has been in the past' (Norris, 1998; xiii). What this tells us is that the sequence of states displayed by Markov systems is driven by a set of random variables that operate in a 'probability space' (Bass, 2011; 1, Billingsley, 1995; 482, Mahnke et al., 2009; 3). An oft-cited example of a Markovian chain is the toss of a coin and its resulting state. Only two states (heads or tails) are possible, and the next state in which the coin will land cannot be predicted by knowing its previous states. Regardless of the sequence of previous results, each toss will always generate a 50% probability for both states to occur. The randomness in the transitions is usually mathematically expressed by a transition matrix used in probability and statistics analysis which, in De Sa's words, aims at finding 'laws of order in the laws of chance' (2006; vi). Knowing the history of the sequences of the coin toss becomes useful exclusively for a stochastic analysis in which probability values are assigned to all the possible future events (Billingsley, 1995; 18).

In other classic examples of Markov chains, such as the Drunkard's Random Walk or the weather, the system can assume a multiple number of next states with an assigned probability. As Tijms (2003; 81-88) explains, the 'future probabilistic behaviour of the process depends only on the present state…and is not influenced by its past history'. In the drunkard’s walk model, for example, a drunkard who can move north/south/east/west has an equal probability of ¼ for next step. The totality of steps taken constitutes the chain, which is a random sequence where each step is solely dependent on its immediate previous one. This random walk model formalizes one of the first stochastic processes observed in nature in 1828 by Robert Brown, who observed how pollen particles released in a water solution would display constant irregularity in their movement. This process, later explained by Einstein in 1905, would become known as Brownian Motion, namely the random ‘motion of a heavy particle in a fluid of light molecules’ (Mahnke et al., 2009; 77) caused by the collisions of the particle with the atoms and molecules of the fluid or gas in which it is suspended. The next state of the particle depends on its current one and the variable represented by the random collisions. Similarly, a simplified weather model over a particular geographic area will every new day assume a specific configuration (i.e. sunny, cloudy, rainy), in a random process not influenced by past configurations.

What appears clear from these first nondeterministic examples is that the element that makes the future behaviour of such systems unpredictable is randomness. While all the possible states a given system can assume are finite and therefore known, random variables render the transition sequences probabilistic. As we will see later in this chapter, Markovian and stochastic processes represent, at this moment, the preferred AI methods in game design to inject diversity among NPC’s actions and behaviour and counteract what would otherwise be repetitive state change sequences with the same user’s input.

2. 5 Nonlinear Dynamical Models of Nondeterministic Systems

A different type of unpredictability can instead be observed in nonlinear systems displaying complex and chaotic behaviour. While stochastic processes respond to questions such as “which of the known states will occur next?”, in nonlinear systems the exact configuration of the next possible future states is unknown. These systems, which evolve over time and are therefore dynamic, are characterized by a strong dependency on their initial conditions and their behaviour ‘never exactly repeats’ (Hilborn, 2000; 7). Slight changes to the starting parameters, as well as small perturbations to the system’s evolutionary trajectory may lead to significantly different future configurations and their aperiodicity make the system’s behaviour look random rather than regular.

The mathematical model for a dynamical system is represented by the time dependence of a point in a geometrical space. As the system evolves over time, the evolution of the point is tracked by an evolution function, which consists of all the variables and parameters which will affect the trajectory of the point in phase space. The dynamical nature of the system implies a continuous change or evolution across the temporal dimension, and its states can be defined at any given moment throughout their succession as expressed by:

$$\mathbf{x}(t) = (x_1(t),\ x_2(t),\ \ldots,\ x_n(t)).$$

where *x* is the state configuration at a specific point in time *t* and is determined by the combined values of the system variables (*x*1, *x*2). In a linear dynamical system, we can expect the changes of trajectory as being proportional to the changes in the parameters governing the evolution of the system. These changes will display in quantitative terms and obey the superposition principle, where if a given input *x*1 leads to the system's response of *y*1, *x*2 will correspond to *y*2 and so on. Furthermore, as explained by Bridgman (1927; 51) the resulting behaviour of a linear system will correspond and be reduced to the total sum of the behaviour of its individual components. On the contrary, the non-linearity at the basis of complex and chaotic systems makes these capable of displaying a type of behaviour that is not reducible to or explainable by means of the laws governing their single components, known as emergent. P.W. Anderson (1972; 393) indicates how 'the behaviour of large and complex aggregates of elementary particles…is not to be understood in terms of a simple extrapolation of the properties of a few particles'. This leads to a wide range of macro-phenomena, ranging from human consciousness, weather configurations, population growth, economic trends or traffic jams to display complex behaviour whose emergence and time-evolution in effect break any prediction attempts based on the analysis of individual constituents. Nonlinear systems can be subject to spontaneous oscillations and aperiodic fluctuations which are not due to external interference or noise, but are caused by 'feedback intrinsic to the system' (Kendall, 2001; 1). Displayed as a graph, the states of an evolving nonlinear system is represented by a point moving in a geometrical plane or phase space generally from left to right, as shown in the figure below which represent the nonlinear path of Earth's temperature over the last eight-hundred thousand years.

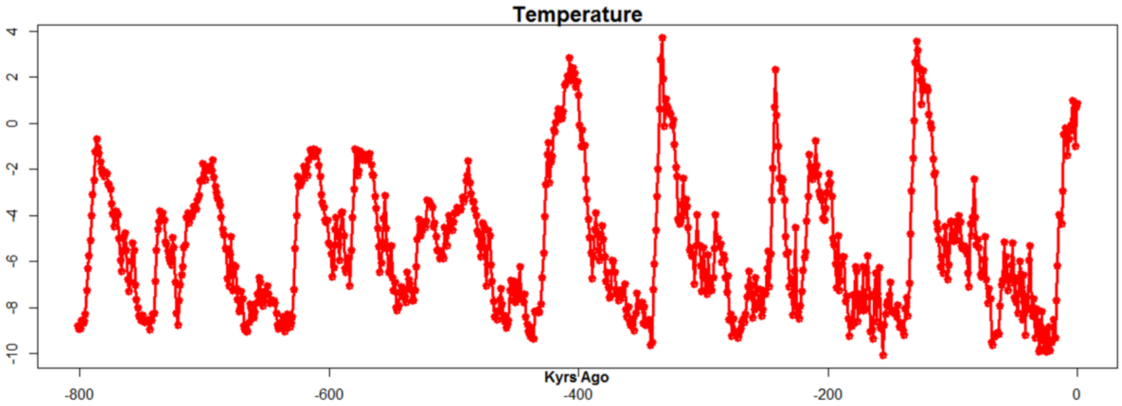


Figure 2. Nonlinear fluctuations of atmosphere temperature through time

The plot of the point in the phase space assumes the form of a trajectory which will move towards areas of the phase space known as periodic, quasi-periodic and chaotic attractors.

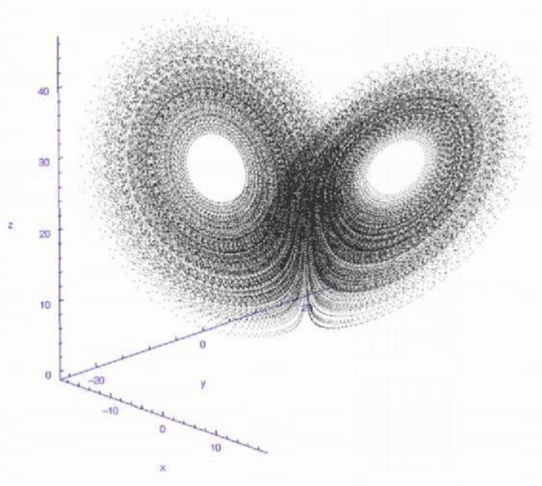


Figure 3. Three dimensional representation of a nonlinear plot with strange attractor

For example, the image above displays a type of chaotic attractor known as strange attractor due to its fractal structure and analyzed by Ruelle and Takens (2001; 63) while studying the behaviour of hydrodynamic turbulence.

With the advent of computing power, and the first significant simulations of models of nonlinear systems, such as Robert May's logistic map of density-dependent population growth (1976), the real chaotic and complex nature of what was once considered as erratic behaviour due to noise was therefore being revealed, with the science of nonlinear dynamics developing to define the properties of nonlinear systems and discovering chaos or complexity even in natural systems once thought linear.

This exponential difference in terms of possible outcomes originating from minor perturbations and changes to initial conditions represents a fundamental feature distinguishing nonlinear dynamical systems from their linear counterpart. Alligood, Sauer and York (1997; vi - viii) explain how the almost erratic behaviour observed in the time evolution of chaotic systems was already evident during the 19th century to scientists and mathematicians such as Maxwell and Poincarè. After the full establishment of the scientific method, and the impact of Newton's classical mechanics, many phenomena in the physical world such as the motion of celestial bodies or the dynamics characterizing the motions of bodies on Earth could be understood and described through differential equations. Aurell et al. (1997; 1) indicate how differential equations seemed to provide the key to understand nature, by revealing, according to Arnold (1983; 250) 'all there is to know about the world'.

Indeed, Laplace's demon was born out of the conviction that, if an entity was to know the exact initial conditions of any system, including the entire universe, then the future could be predicted with complete accuracy. However, while differential equations sufficed in solving linear scenarios and describing the behaviour of steady state systems displaying regularity and systems in constant motion and subject to periodic or quasi-periodic oscillations, a third type of system behaviour seemed to escape complete long term predictability. This was not due to a large number of periods displayed by a system or its large number of interacting particles and components, but to high sensitivity to the initial conditions. Maxwell reported the example of a simple system consisting 'of two colliding gas particles in a box', whose long-term motion and behaviour 'would for all practical purposes be unpredictable' (Alligood et al., 1997; vi). Similarly, Henri Poincare' described, in the famous 'three-body problem', how differential equations employed to solve the gravitational interactions of two orbiting masses would not be sufficient in predicting the future trajectories and positions of a seemingly simple star system comprising two large bodies and a third body of negligible mass, such as an asteroid. He discovered that the periods or orbiting motions of the three bodies could be subject to near-collisions, known as ‘homoclinic crossings’ (Alligood et al., 1997; 48) or bifurcations, after which any periodicity would be lost and the behaviour of the system would become unpredictable. High sensitivity to initial conditions, exponential diversification of outcomes and impossible long-term predictability are all features of complex and chaotic systems. These consolidated into a new field of investigation during the 1970s, with the advent of computer graphics that made it possible to run simulations that would visually display the evolution of a system over time and would also facilitate the modification of the initial parameters, with the consequences being directly observable on the screen.

We have seen how an important characteristic observed in chaotic systems is the nonlinearity, which states that the system’s behaviour will not be proportional to the values of the perturbations and changes in the initial conditions. However, Hilborn (2000; 7) explains that the behaviour of these systems can, in principle, be predicted by knowing 1) the time-evolution equations, 2) the values of the parameters describing the system and 3) the initial conditions. In practice, however, these systems can have several ‘degrees of freedom’, or the number of possible directions in which the system’s trajectory can move. Furthermore, in many cases of phenomena observed in nature, it becomes difficult to have exact knowledge of the initial conditions, and ‘infinitesimal perturbations grow exponentially with time (Aurell et al., 1997; 2). The weather is a frequently used example of a dynamical chaotic system presenting many challenges not only to long-term predictions, which always bear large approximations even in short time lapses, but also to localized phenomena. For example, Aurell et al. explain that, while large-scale predictions of the weather at temperate latitudes can be valid for a 10-day time range, ‘how the wind blows on the corner of the street is in practice unpredictable from one moment to the next’ (1997; 2).

Edward Lorenz (1993; 22) mentions the pinball machine as a simplified example of a chaotic system in which the direction of the ball becomes hard to predict due to the intricate net of interactions of all the variables governing the game. The interaction of factors such as the ball’s spin, velocity and current direction with the effect of friction, the angle of impact on the pin and the resulting bounce, for example, leads a pinball player to constantly having to readjust his or her predictions on where the ball will hit next. If we take the path of the ball leaving the plunger, this will vary at each game. Any slight change in the initial parameters, such as for example the intensity used to thrust the ball, will amplify the path exponentially. In nonlinear chaotic systems, once a parameter is varied, the system's undergoes a sudden change of behaviour which is known as 'bifurcation' (Hilborn, 2000; 13), which leads to a qualitatively different outcome. Another example comes directly from the current configuration of the universe, whose properties and complexity (in the form of life) is believed to be the result of an extremely precise fine-tuning of its initial conditions. Hawking notes how several fundamental numbers such as the charge of the electron, the strength of the nuclear force, and all values attributed to the physical laws of nature 'seem to have been very finely adjusted to make possible the development of life' (1988; 125). What this tells us is that slight changes to any of these values in the initial conditions of our universe would cause a bifurcation with qualitatively different outcomes which would, for example, preclude the emergence of life, the existence of galaxies and stars or even the aggregation of molecules or formation of atomic nuclei. In the "multiverse" solution to the fine-tuning, astronomer Sir Martin Rees (1999) explains how infinite universes, beyond our observational horizon, emerge each carrying their own physical laws governed by different values, making their configuration very different from each other. Lorenz indicates how the sensitive dependence of chaotic systems leads to the 'impossibility of making perfect predictions, or even mediocre predictions sufficiently far into the future' (1993; 11-12).

2.6 The Cellular Automaton Model

Chaotic systems displaying an apparently random behaviour are paralleled by nonlinear complex systems capable of displaying emergent and intelligent behaviour, also known as Cellular Automata. Processes such as these, that are capable of generating complexity and unpredictable behaviour, derive their origins from the experiments with elementary Cellular Automata by James Horton Conway in the *Game of Life* (1970), and were later on formalized and divided into classes in Stephen Wolfram's studies of automata theory and used as a new perspective to understand and explain complexity in nature and the universe.

According to Wolfram's *New Kind of Science,* (2002), Cellular Automata are a collection of coloured cells on a grid of specified shape that evolves through a turn-based step system according to a set of initial rules and conditions based on the states of the neighbouring cells. Below is an example of a two-dimensional Cellular Automata in which each coloured cell on the grid represents a live automaton whose state in the next turn will depend on the position of its neighbours and the initial rules governing the interactions among the automata. A typical configuration can be seen in figure 4:

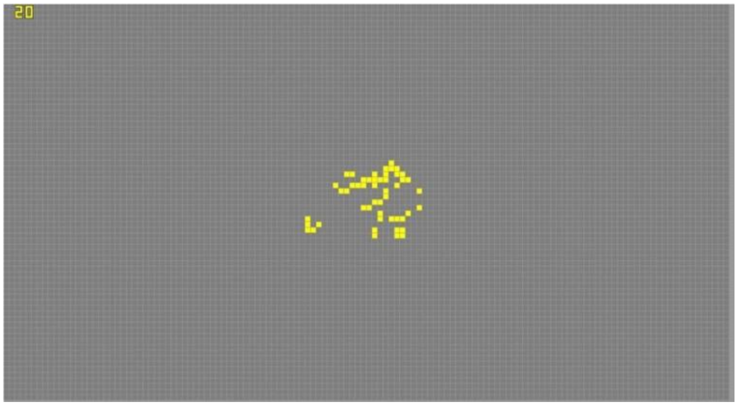


Figure 4. Two dimensional Cellular Automata on a squared grid

Once the rules are established, and the simulation is initiated, no further input is necessary, and it is sufficient to observe how the automata evolve on the screen over time. In Conway's *Game of Life*, 'the birth, survival and death of individuals is a function of their own state and that of their neighbours' (Luger, 2009; 508). If a cell is surrounded by a specified number of other cells, it may die (overcrowding or sparse population). Likewise, it may survive with the proper conditions. Poundstone (1985) notes how *The Game of Life* shows how from simple initial conditions, a rule-based system of automata can give rise to seemingly autonomous behaviour, complex group behaviour, self-replicating processes and what appear to be multi-cellular organisms. Underlying these processes and determining the automata movement and behaviour is an evolutionary law of survival, affecting in this case the interactions between neighbours. Unlike what we will later observe in genetic algorithms and artificial neural networks used in AI, Cellular Automata in the *Game of Life* have no fitness ranking system, and there is no explicit learning algorithm teaching them how to survive. On the contrary, 'learning among cellular automata is typically unsupervised' (Luger, 2009; 531), and further generations seem to retain the successful behaviour of previous ones. Each generation, or life cycle, coincides with a turn. Emergent complex structures such as the "gliders" that move across the grid through each generation have been observed as an unexpected phenomenon of rich collective behaviour, and ‘have proven a powerful tool for studying the mathematics of the emergence of life from simple, inanimate components’ (Luger, 2009; 532).

Chaotic and complex systems offer a way of injecting unpredictability and novelty in game design due not only to the fact that the outcomes these systems may evolve into are unknown, but also to complex behaviours which may lead to interesting situations from a game’s narrative point of view.

Chapter 3. Complex Emergent Behaviour: *The Game of Life*

'People think mathematics is complicated', comments John H. Conway in Martin Rees' documentary *What We still don't know* (2004) which addresses questions regarding the origin of complexity in the known universe:

"mathematics is the simple bit, it's the stuff we can understand. It's cats that are complicated. I mean what is it, in those little molecules and stuff that make one cat behave differently to another? Or that make a cat? And how you define a cat? I have no idea…"

3.1 History and development of the *Game of Life*

By using an example of organic life, what Conway is hinting at is the complexity of behaviour observed among living organisms, and the difficulty in understanding the mechanisms governing this diversity. In the previous chapter, we have observed how some non-deterministic, more specifically nonlinear dynamical systems, can display complexity and diversity of behaviour which make their long-term predictability impossible. This property marks a significant distinction in comparison with the other category of nondeterministic systems such as stochastic and Markovian models whose state sequences are governed by a probabilistic architecture. In our search for a model which can overcome the finite and deterministic nature of narrative structures in video games, an essential factor to consider lies in our understanding of what the long term outcomes of nonlinear dynamical systems and probabilistic systems can be.

We have seen how, in probabilistic systems such as the drunkard's walk, the toss of a coin or a roulette spin, the future states are memoryless and do not depend on the past states. Random variables will render the transition to the next state only partially known through an assigned probability value. Indeed, in this case the number of possible states is finite and known in advance. The intrinsic uncertainty guiding the next transition is therefore paralleled by a complete certainty of which states the system can assume. The number of possible outcomes is discrete and the nature of the states is fixed and unchanging. On the other hand, in nonlinear dynamical systems such as Cellular Automata, due to their internal complex interactions and high sensitivity to the initial conditions, it becomes impossible to determine what type of state the system will assume next, thus revealing an open-ended type of unpredictability. As we will see in this chapter with the example of Conway's *Game of Life*, Cellular Automata may reach static configurations (still life), repeating patterns (oscillators) or nomad and reproducing structures (spaceships, gliders). Furthermore, the location on the grid and time-frames at which transitions will take place are unpredictable, with CA populations being able, for example, to stabilize or disappear after an unknown number of generations.

In transferring the notions of probability and unpredictability of outcomes deriving from these two types of nondeterministic systems to the context of simulation and game design, what will become clear is that, since stochastic techniques have been long implemented in game AI to inject a controlled degree of diversity of NPC behaviour and reduce repetitiveness, it is necessary to adopt elements from nonlinear and complex systems. This is particularly true if we are to elaborate a model aiming at not only creating significant diversity among the possible narrative outcomes of a game title beyond the mere reshuffling of existing possibilities, but also providing an element of surprise and openendedness regarding the very nature of narrative events which would present strong dependency on the initial conditions (customizable by the player) and internal dynamics beyond the player's control. Furthermore, by looking closely as we will in this chapter, at a specific type of nonlinear dynamical system, the Cellular Automata in Conway's *Game of Life*, we will be able to gain important insights about the variety of outcomes generated by tweaking the initial rules and conditions.

In the previous chapter, we have seen how the degrees of freedom characterizing these systems allow for slight changes to their initial conditions and small internal perturbations to lead to bifurcations in the system's evolutionary dynamics after which any periodicity is lost, and attempts to recognize future recurrent patterns or states would be futile. Many systems in the physical world such as weather, fluid dynamics or the Brownian motion, as well phenomena such as traffic, economic trends and population growth display nonlinear chaotic behaviour and appear to have seemingly erratic developmental trajectories. In addition, when looking at the realm of living organisms and the complexity of the phenomenon of life, another property appears in the form of emergent and intelligent behaviour. In the preface to his *Introduction to Artificial Life* (1997), Adami indicates that while complex physical systems can in theory lend themselves to analysis by being deconstructed and studied in its single constituents, ‘in almost all cases, a deconstructed living system is no longer alive’ (i). The complex behaviour of life and the emergence of intelligence, therefore, cannot be explained by analyzing the single components of a given organism. Adami continues by saying that further approaches to the study of life and complexity assume ‘that there is a universality in the processes that give rise to life’ and that ‘given this universality, life can be implemented in any medium that can give rise to such processes’ (1997; ii). It is this very idea that was adopted by English mathematician John Horton Conway during one of his mathematical quizzes and puzzles. Driven by the conviction that complexity had to arise from simple initial rules and extensively experimenting on mathematical games, as in his collection of games *On Numbers and Games* (1976), Conway started to experiment with several possible initial configurations and sets of rules governing the evolution of the discrete computational and mathematical model of Cellular Automata. These were introduced for the first time by Von Neumann during the 1950s in his *Theory of Self-Reproducing Automata*, eventually published in 1966 after his death. Conway soon discovered that by assigning initial rules loosely based on genetic and evolutionary laws, such as birth and survival or death by isolation and overcrowding, interesting patterns would emerge leading to unpredictable complexity and to seemingly purposeful types of behaviour displayed by the cells or automata. According to Gardner (1970; 120), ‘because of its analogies with the rise, fall and alternations of a society of living organisms’, Conway’s invention was seen as a life simulator, therefore named the *Game of Life*.

Indeed, the genetic algorithm governing Conway’s simulation is capable of generating, as we will see, a wide variety of self-organizing structures whose evolution is no longer subject to randomness or stability, but shows, as pointed by Gardner, analogies with population growth and self-preservation. In this chapter an in-depth analysis of Conway’s Cellular Automata will be provided. An historical overview of Conway’s work, along with a discussion of the rules and outcomes of the *Game of Life* will be followed by the interpretation of the cellular automaton as a particular type of nonlinear system. Examples from existing studies will then follow stressing the nonlinear nature of evolution.

Understanding the mechanics of the *Game of Life* and its analogies with the emergence of complex behaviour observed in natural phenomena as well as among living organisms will set the premises for the development of a model for a nondeterministic application proposed in this study to be integrated with game design.

In the October issue of *Scientific American* in 1970, popular mathematics and science writer Martin Gardner was reviewing in his column dedicated to mathematical games what he considered to be John H. Conway's latest game known as "life". This was the first public appearance of Conway's recreational puzzle which would soon generate not only curiosity and interest among mathematicians and computer scientists, but would also come to represent an alternative approach for understanding the emergence of complexity in natural and biological phenomena as originating from basic starting rules and conditions. In this regard, Bays (2010; 1) confirms that 'the single feature of his "game" that probably caused this intensive interest was undoubtedly the discovery of "oscillators" (periodic forms) and "gliders" (translating oscillators)'. What this meant was that the basic initial rules set by Conway could somehow give inanimate objects, in this case elementary onedimensional cells having only two states (on/off), the ability to form patterns and structures which were not simply random, but could at times coalesce into intricate shapes, travel across the two-dimensional grid in a purposeful rather than erratic manner, resembling simple living organisms driven by the instinct of survival across the generations. According to Adami (1997; 4), observing the global behaviour of CA (Cellular Automata) would confirm the notion of life as a complex emergent phenomenon, or a 'property of a *collection* of components but not a property of the components themselves'.

While the interest triggered by Conway's game, in conjunction with the increasing accessibility of home computers throughout the 1970s and early 1980s, would give rise to the field of Cellular Automata studies developed primarily by Stephen Wolfram in *A New Kind of Science* (2002), the model of the cellular automaton adopted by Conway was itself a simplified version of John Von Neumann's model elaborated during the 1940s as a theoretical basis for the Universal Constructor. Thatcher (1970; 132-136) McMullin (2000; 347) indicate how during the 1940s and through the next decade, Von Neumann was beginning to work on a theory of Cellular Automata that would represent the blueprint for the mathematical model of an automated machine able 'to construct in a given environment everything that can be materially produced by any other machine in the same environment' (Nobili&Pesavento, 1994; 3). Therefore, the universality of the machine derived not only from the ability of emulating any other type of machine, but to build copies of these through taped instructions and extended so as to include the possibility of building copies of itself. Von Neumann's attempt was to expand on the concept introduced by Alan Turing in 1936 of universal computing capability, and he eventually designed a model of Cellular Automata in which each two-dimensional automaton had a 29-state specification. Preston and Duff (1984; 2) explain that in Von Neumann's work, Cellular Automata served as an abstract formalization of his vision of a concrete computing assembly where each automaton represented an array of identical computing units 'with each connected to its immediate neighbours'. By reading instructions from a tape describing a 'quiescent cell assembly' (Pesavento, 1995; 338), the automaton could reproduce the dormant cell assembly in a nearby blank field and finally activate the quiescent newly-built cell assembly and instruct it to perform the same operations. However, Von Neumann's design was considered prohibitively complex (Thatcher, 1970; Langton, 1984; Nobili&Pesavento, 1994; Pesavento, 1995). It also did not explicitly address the logical question of how machines of higher complexity could be built by machines with lower complexity.

While an element of mutation between generations of automata was added to the taped instructions, and this will be highly relevant to our application in game design, McCullin (2000; 351) indicates how this did not suffice in accounting for the 'pragmatic experience of machines and engineering' pointing in the opposite direction, where a certain degree of complexity would necessarily require a higher or at least equivalent degree of complexity in order to be produced. Nevertheless, by proposing the first practical design for a universal constructor, Von Neumann had not only posed the challenge for understanding 'the minimal logical requirement for self-reproduction' (Nobili&Pesavento, 1994; 3), but also the problems of complexity and evolution in a Cellular Automata framework. Several attempts at iterating Von Neumann's model would follow, with the tendency of decreasing the complexity regarding the possible number of states and state transitions for each automaton. Pasavento (1995; 337), who along with Nobili implemented and completed Von Neumann's model in 1995 by elaborating a 32-state CA model, explains how later experiments by Moore (1970), Thatcher (1970), Thatcher and Wright (1968) and Codd (1965, 1968) all opted for a reduction of states and transitions, with a consequential increase in the total number of individual automata and of the global structure, eventually proving that 'constructive universality can be assured for cellular automata with fewer states' (1994; 3). This search for a simplified model with fewer states and transitions, caused by the difficulty in implementing real-world models of a universal constructor or computer, also led to an increasing interest in the initial rules determining the overall evolution and replication of automata and therefore in the 'morphogenetic and dynamic properties' (Nobili&Pasavento, 1994; 3).

It is during the late 1960s that we can witness the beginning of a theoretical approach towards Cellular Automata as dynamical systems with rule-induced behaviour, and it is in this context that the *Game of Life* would eventually develop. Preston and Duff (1984; 10) explain how in 1967 Schrandt and Ulam 'became intrigued by the patterns formed by the groupings of 1-state-elements and 0-state-elements at various stages of the computation'. The 1 and 0 state elements represented the only two possible states –on/off, dead/alive- into which the automata could transition according to the type of rules established at the beginning of the simulation. They were also experimenting with different sets of initial rules based on the life and death of a given cell in the next generation as depending to how many live neighbours it had at any one time. In this regard, Schiff (2008; 92) describes the 'dog bone configuration' discovered by Srchrandt and Ulamduring the 1960s at Los Alamos. This represents one of the first accounts of simulations made on early electronic computers showing Cellular Automata expanding on a screen. (Ulam, 1986; 78). As Ulam describes (1962; 217), fine tuning the initial rules soon led to the dog bone assuming 'the six-fold symmetry of the original figure', thereby displaying fractal properties. Experiments investigating the effects of initial rules upon the development of the automata on two or three-dimensional grids started to proliferate thanks to the accessibility of computing processing power. To this regard, Wolfram (2002; 24) recounts how one of the main reasons he approached CA simulations was not only their simplicity, but also the fact that 'their behaviour can readily be presented in a visual way'. Cellular Automata simulations could now be made to run automatically in the background until some significant results could be observed, and with their dynamical activity being constantly recorded and displayed visually on the computer screen. We have seen how Schrandt and Ulam were already observing ‘computer-generated patterns exhibited by “figures” growing according to certain recursive rules’ (1967; 3).

The mathematical abstract modelling of Cellular Automata, introduced decades earlier by Von Neumann to represent the architectural blueprint for a real self-reproducing machine, was now showing potential for the wider notions of growth, evolution and self-organization, expanding its scope of application beyond mathematics and to a wide variety of fields like biology, chemistry, computer science, artificial intelligence, engineering and architecture. This also helps us define and clarify the nature of Cellular Automata simulations as a mathematical model, often translated into a computer program, whose primary purpose is not that of imitating or reproducing in detail all the functions and mechanics of a particular system, but rather to propose an abstract configuration to capture the fundamental mechanisms that drive the formation of complexity observed in many systems in the physical world. While not re-creating the system itself, CA simulations have contributed, for example, to the growing conviction that the properties of nonlinearity, unpredictability and intrinsic randomness are at the basis of several chaotic and complex systems such as fluid dynamics, growth and evolution of biological organisms and ‘all sorts of complex behaviour in nature’ (Wolfram, 2002; 11).

In Wolfram’s interpretation, Cellular Automata are approached as the digital representation of how nature creates complexity from simple initial instructions. They offer a bottom-up dynamical representation that not only emphasizes rule-simplicity, but also makes experimentation widely accessible due to its low resource consumption and easy implementation. This is in contrast with a top-down, opposite approach adopted in current computer graphics technology regarding physics and complex system simulations, which has its widest application in game design. For example, latest physics engines such as Nvidia’s PhysX, or the most recent FLEX, rely on complex computing algorithms employing Rigid Body Dynamics or Position Based Dynamics (Muller, 2008; 1). In this case, the attempt is to deconstruct a complex system, with every particle forming a complex fluid or rigid body being handled individually by the engine which constantly calculates the changing properties, such as position and velocity, of the individual components. The final result is an improvement in the visual plausibility of a complex system at the cost of expensive resources and technology. Although these engines are ‘capable of capturing several aspects of the system more realistically’, explains Coutinho (2013; 4), they remain

‘simple first-order approximations’ giving a ‘sufficiently accurate feeling of authenticity’.
In this regard it must be pointed that current physics engines do not create but rather imitate complexity for visual and interactive fidelity within the close boundaries of pre-determined game scenarios. They follow what Wolfram considers as an intuitive engineering logic (2003) where initial complicated plans are implemented in order to create a complicated system whose objective is to display specific functions and behaviours known in advance and free of any randomness or unpredictable outcomes. A ship floating on an ocean as observed in *Assassin’s Creed IV* (Ubisoft, 2013) for example is the result of a careful recreation of the complex fluid dynamics occurring in the real world which remains subject to controlled parameters. In this case the aim is to provide only a snapshot and visual credibility of the complexity of the ocean motion and maintain at the same time control over the events of the game so that the ship, for example, will never capsize and therefore disrupt sequences in which pre-determined series of events are set to occur. On the other hand, Cellular Automata can instead shed light on the fundamental rules necessary to generate complexity and would therefore have a different and deeper impact on the very development and behaviour of game entities.

Wolfram demonstrates, for example, how rules can be set for two-dimensional CA in order to represent the complex pattern of a snowflake in thirteen time-steps as shown below:

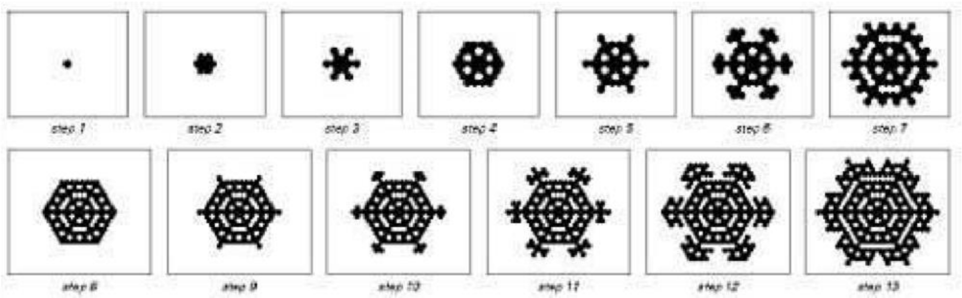


Figure 5. Evolution of two-dimensional Cellular Automata emulating the structure of a snowflake

However, he also reminds us that Cellular Automata are there to capture ‘certain essential features of a system, and idealize away everything else’, and they ‘are not supposed to be the system itself’ (2003). In this light, Cellular Automata can bear a number of similarities to the Finite State Machine models discussed in the previous chapter, with both models attempting to capture the essential mechanisms of systems observed in nature. One fundamental difference, however, is represented by the non-deterministic and open-ended nature of Cellular Automata and their simple rules as compared to the close-ended and controlled nature of Finite State Machines which can have intricate interactive architectures. If Finite State Machines aim at proposing a model for predictable systems such as liquid state transition or automated teller machines (ATM), CA offer a model for non-predictable systems in which complexity can arise. In the wider context of this study, the potential of CA models to pave the way for non-deterministic narrative structures in game design appears justifiable.

According to Krawczyk (2003; 1), in the context of computing and simulations, Cellular Automata could simulate ‘the process of growth by describing a complex system by simple individuals following simple rules’. Indeed, it was this potential for simple 2-state entities interacting through simple rules to reach levels of structural and dynamical complexity to attract the attention of scientists and mathematicians such as Conway. Schrandt and Ulam (Preston&Duff, 1984; 10) were starting to observe how, while certain sets of rules would lead to the death of the automata population, with all cells switching to the off-state, to the opposite result or to the formation of static and repeating patterns, a fine-tuning of the initial rules could cause the automata to display ‘phenomena of both motion and some selfreplication’ (1967; 3). These phenomena carried a degree of complexity that could not be predicted beforehand and would pose a challenge to the logical assumption of complex structures requiring complex generating rules. Indeed, as Wolfram notes (2002; 23-24) patterns of on/off states of different but uniformly distributed shapes deriving from the implementation of certain simple initial rules would easily lead to the assumption that ‘any rule we might choose would always give a pattern that is quite simple’. The essence of this simplicity-to-complexity dynamics embedded in Cellular Automata simulations was permanently captured by Conway’s mathematical game, which, partly thanks to Gardner’s review in the *Scientific American*, led to a widespread popularity beyond academia which continues to this day with several on-going Cellular Automata simulation projects. The direction towards simplicity of states and rules, along with the curiosity generated by the unpredictability of how and in which patterns automata would behave and develop, led Conway to adopt the most simplified Cellular Automata simulation model where to implement basic rules inspired by genetic laws of birth, death and survival.

The Game of Life consists of a two-dimensional grid made of squares of equal dimension which can extend indefinitely in all directions. Each square represents the space coordinate on the grid on which the automaton can exist and, in the case of Conway's simulation, can display one of the two possible states: on/off. In his review Gardner describes the noncomputer version of the game, consisting of a 'fairly large checkerboard and a plentiful supply of flat counters of two colours' (1970; 120). The counters represent the onedimensional cellular automaton, which generally appears as a black or white pixel in computer simulations. Whether displayed on a computer screen or on a real board, this configuration represents the most common visual representation of Cellular Automata, also known as space-time pattern field.

A most common representation of Cellular Automata in a computer simulation environment can be seen in the following screenshot:

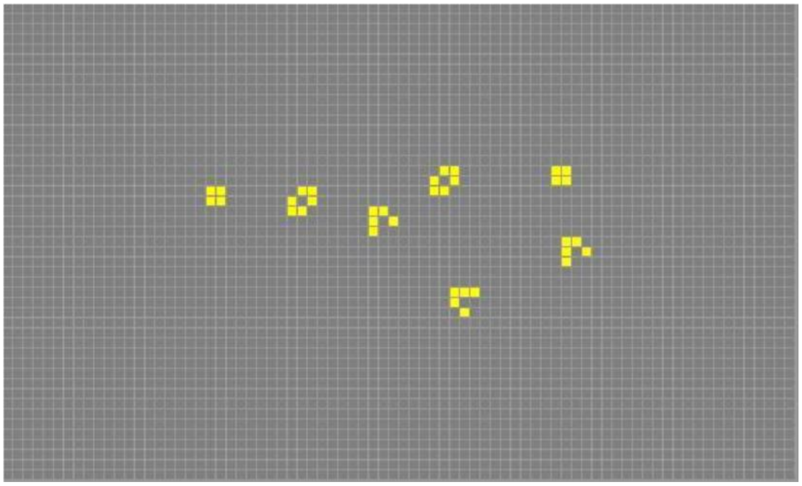


Figure 6. Visual setup of the freeware *Game of Life* simulation program

In figure 6 all elements constituting Conway's simulation are represented, in a specific structural formation, known as Gosper Glider Gun, which shows a certain degree of complexity and which will be addressed later in this chapter. Each single square cell is a potential automaton which can be in one of two possible on/off states. The live automata appear as coloured cells, as opposed to their blank counterpart. The grid itself represents the space-time field containing the dynamical evolution of automata. When simulated on a computer, the two-dimensional grid can extend infinitely in all directions using a technique known as procedural generation. This method, applied in its basic form in two or threedimensional Cellular Automata simulations, takes advantage of a class of algorithms enabling the graphics engine to produce visual content automatically once the boundaries of the screen are being reached. In the case of Cellular Automata, the coordinates of the spacetime field will therefore extend indefinitely in all directions for as long as any type of Cellular Automata activity is detected. This feature not only accelerates exponentially the results of CA simulations, but also allows for a detailed observation of the history of the development of Cellular Automata as a dynamical system and makes it possible to preserve a recorded screenshot of every generation and time-frame during their evolution. Furthermore, several levels of zoom can be applied to facilitate the understanding of the dynamical activity, as shown in the screenshots below:

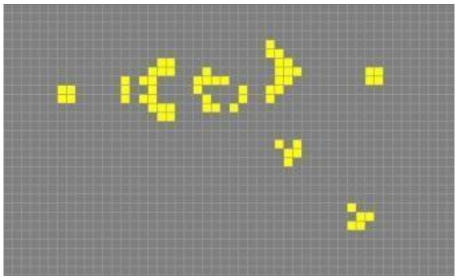


Figure 7a. Close-up picture of Glosper Gliding Gun

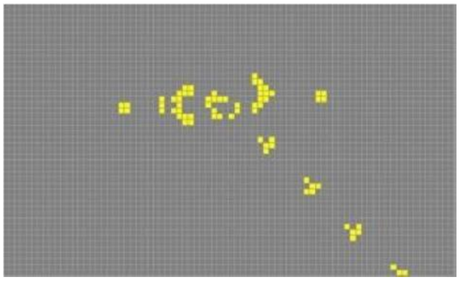


Figure 7b. Medium close-up of Gosper Gliding Gun

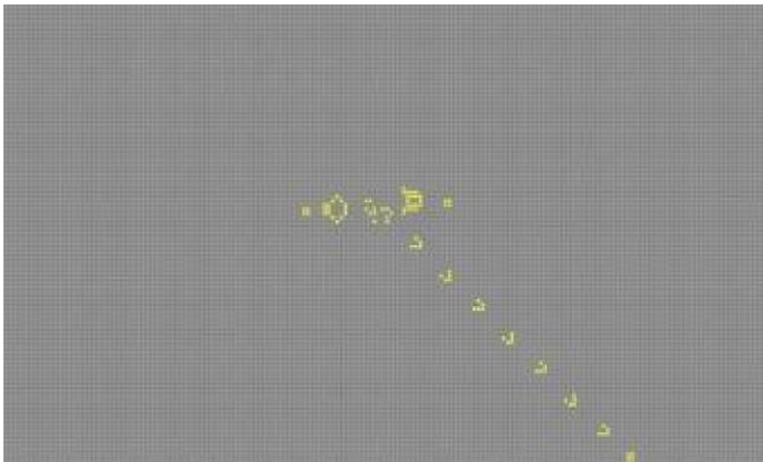


Figure 7c. Enlarged picture of Gosper Gliding Gun showing more activity

The three figures show the same time-frame of the above mentioned Gosper Glider Gun from three different perspectives. The pockets of activity shown in the first frame are part of a wider dynamical behaviour which can be observed in the zoomed-out frames of figure 7b and 7c. In this case the results involve the formation of moving repeating patterns, known as translating oscillators, which move toward the lower part of the grid and will continue to live for an indefinite number of generations.

As explained by McIntosh (2010; 35), in the *Game of Life* certain configurations can go through a large number of cycles before stabilizing into static shapes (still life), repeating patterns (oscillators), long-lived structures (methuselah) or repeating patterns that continue to move along the grid (translating oscillators). For example, the complex, aperiodic behaviour displayed by Wolfram's Rule 30 requires a large number of time steps before coalescing into the intricate nested patterns visible in the figure below:

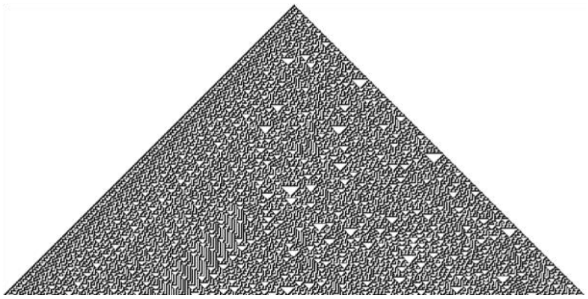


Figure 8. Intricate patterns of Rule 30 generated after five hundred steps

Returning to Conway's initial configuration, each square can be visualized as being touched by eight possible immediately surrounding neighbours. Known as Moore Neighbourhood (Bays, 2010; 1), the eight-neighbour array was an extension of Von

Neumann's initial four-neighbour model and was originally implemented by Moore in 1956 in his application of the Universal Constructor theory to a model of self-replicating artificial living plants. Moore (1962; 21) explains how his configuration, where all cells 'have each of their coordinates differing by at most 1 from the coordinate of the given cell', would lead to a rectangular, rather than diamond-shaped cell-array and would render it 'easier to compute the number of cells in certain arrays'. Aside from computational and visual differences, the Moore neighbourhood represents the only viable configuration in which

Conway's rules for the *Game of Life* assumes validity and can therefore be fully implemented. The evolution and dynamics of the Cellular Automata develop through a discrete time-unit progression system where the initial rules are recursively applied at each time-step, and where each time-step represents a generation of automata. The manual replacement and addition of dead or alive counters on the checkerboard as generations succeed becomes an automatic process when the Game is run on a computer. Once the rules are defined and the simulation has begun, no further input is necessary and one can observe how patterns form and evolve over an indefinite amount of time.

In Conway's simulation, there are three fundamental starting rules that will apply recursively to all generations as the time-step sequence is initiated. It is important to specify that these rules will be valid for all cells present on the grid (whether blank or populated) and will govern the rate of birth of blank cells and the survival (or death) or live cells simultaneously as explained below:

Birth:

1) If a blank cell is touched by three adjacent neighbours, it becomes populated (comes to life) and therefore switches to its "on" state in the next generation

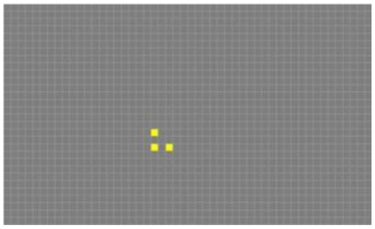


Figure 9a. Central blank cell surrounded by three live neighbours

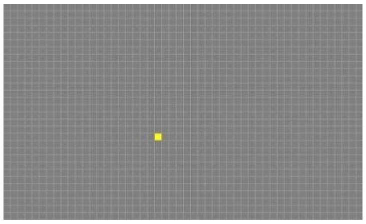


Figure 9b. The blank cell becomes active

In figure 9a the necessary conditions for a cell to become populated in one generational step are represented by the three coloured cells surrounding a central inactive cell. As figure 9b shows, after one time frame, the central cell previously surrounded by the three neighbours has become active, with the previously alive cells vanishing due to isolation. 2) If a blank cell is touched by more or less than three neighbours, it will remain blank (unborn), as by overpopulation, in the next generation

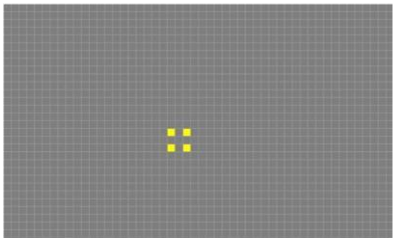


Figure 9c. Central blank cell surrounded by four neighbours

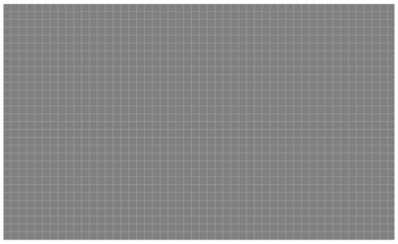


Figure 9d. The blank cell stays inactive due to overpopulation

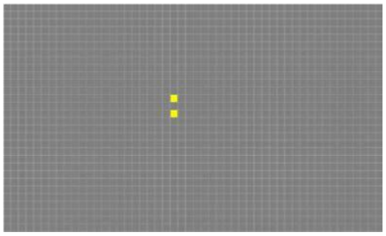


Figure 9e. Blank cell surrounded by two neighbours

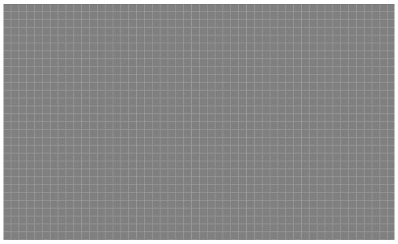


Figure 9f. The blank cell stays inactive due to isolation

In figures 9c the central inactive cell is surrounded by four neighbours. The next time frame shown in 9d is the consequence of the second rule which causes overpopulation to prevent the birth of a new cell. Same results of unborn cells are observed in figures 9e and 9f where two live neighbours do not fulfill the condition for cell population.

3) If a blank cell is touched by less than two neighbours, it will remain blank, as by isolation in the next generation

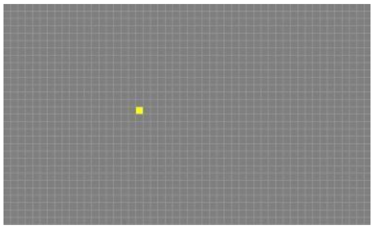


Figure 9g. Single live cell

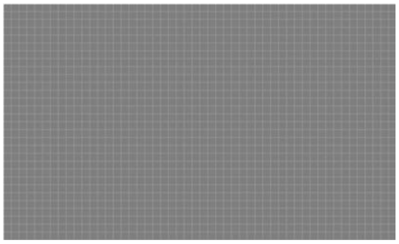


Figure 9h. The live cell dies by isolation

All the empty cells surrounding their only populated neighbour in 9g will stay as such in the next step 9h due to the third isolation rule.

As indicated above, the three rules also determine the survival or death rate of all live cells:

1) Every activated cell with two or three neighbouring live cells will survive to the next generation

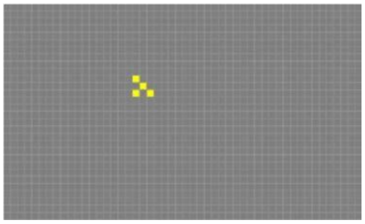


Figure 9j. Live cell with three neighbours

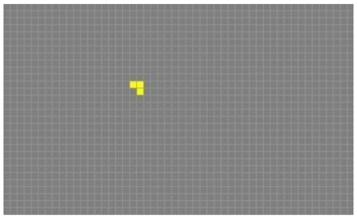


Figure 9k. Live cell survives at the next step

In figure 9j a central live cell is shown being touched by three neighbours. This allows the cell to continue on to the next generation, shown in 9k, where also two of the previous neighbours survive.

2) Every activated cell having more than three live neighbours will not survive to the next generation and will disappear from the grid

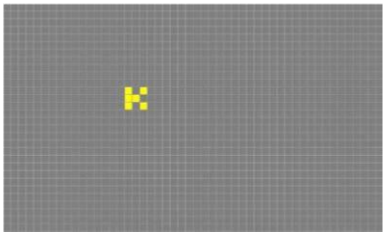


Figure 9l. Live cell with four neighbours

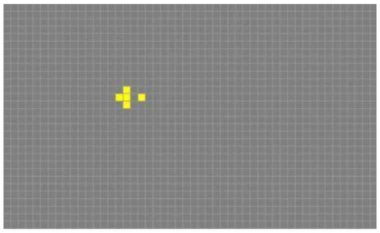


Figure 9m. Live cell dies due to overpopulation

In 9l it is possible to observe how the central cell is surrounded by an excessive number of neighbours. During the next step shown in 9m, a number of cells, including the central one, do not survive as per overpopulation, while two new cells meeting the right conditions for birth appear.

3) Every activated cell having less than two neighbours will also not survive to the next generation

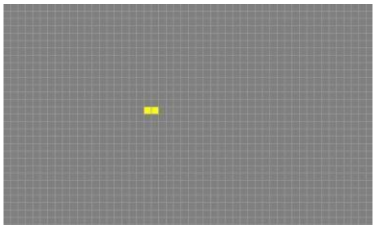


Figure 9n. Live cell with one neighbour

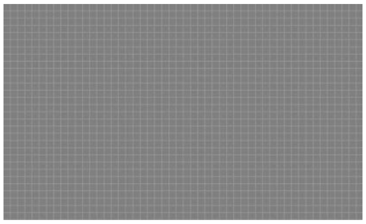


Figure 9o. Live cell dies to isolation

Finally, the two live cells shown in 9n are each other's only neighbours. As a consequence, both cells will die at the turn of the next generation as shown in 9o.

As explained by Gardner (1970; 120) and Bays (2010; 2), the rule discovered by Conway was labeled as rule 2/3/3, and became popular primarily for its ability to give rise to interesting shapes and patterns displaying complexity and unpredictable behaviour.

Conway's discovery was the result of an extensive tweaking and fine-tuning of his observations on the nature of the rules governing biological processes. As Gardner explains, Conway enforced simple genetic laws by focusing on principal factors such as birth, survival and death. Upon choosing the initial conditions, Conway ensured that the following criteria were met:

a) There should be no initial configuration that leads to an explosive growth. Explosive of limitless growth indicates the ability of the cells to grow beyond the limit represented by the finite number of squares in the grid. While Conway assumed that there were no patterns capable of displaying such behaviour, Bill Gosper, shortly after Gardner's review of the *Game of Life*, discovered in the same year the Glider Gun which constituted the first example of unbounded growth. Bays explains how Gosper 'devised a form that spit out a continuous stream of gliders' (2010; 4), paving the way for other similar patterns later discovered.

b) There should be initial configuration that can develop and grow without limit, eventually stabilizing into oscillators or permanent periodic moving patterns.

c) There should be simple initial patterns that grow and evolve through a large number of generations before stabilizing into three types of final configurations. These are represented by the live cells vanishing (extinction), coalescing into static structures (still lifes) or 'entering an oscillating phase in which they repeat an endless cycle of two or more periods' (Gardner, 1970; 120).

Upon further experimentation, it was soon discovered how clusters of automata could transform into a rich variety of shapes, often assuming 'rather whimsical names' (Bays, 2010; 3), according to their behaviour and the real-life objects they resembled, such as heavy-weight or light-weight spaceships, puffer-type breeders, lobsters, diehard and pulsars as well as the gliders initially discovered by Conway himself in 1968. Nevertheless, among the wide variety of shapes, three major configurations can be distinguished according to their overall behaviour:

1) **Still Lifes**: these are stationary formations that reach their final static configuration after a period of ‘n’ generations and maintain it indefinitely.

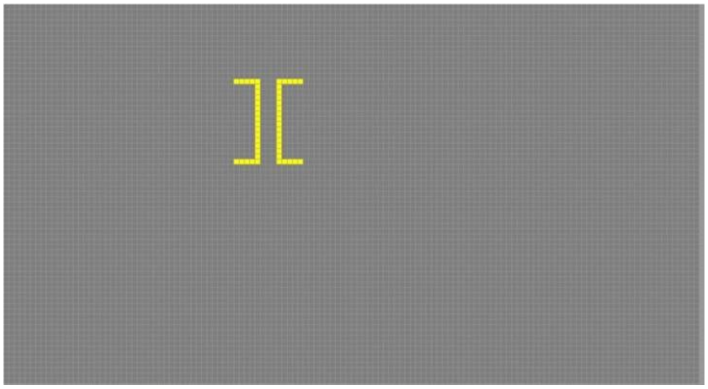
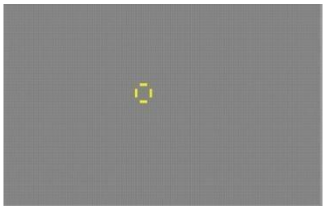
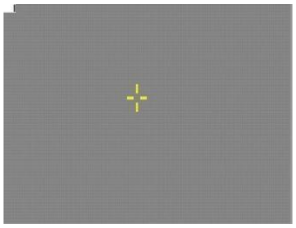


Figure 10. Example of static still life

2) **Oscillators**: clusters of automata which fall back into a specific shape after a period of two generations. Like still lives, oscillators do not travel across the grid and tend to stay permanently in the same space field coordinates.





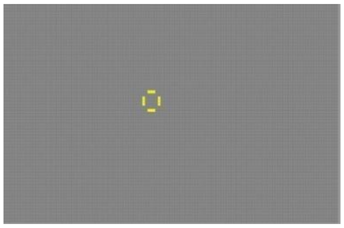


Figure 11a. Oscillator-period I **Figure 11b. Oscillator-period II** **Figure 11c. Oscillator-default**

3) **Translating Oscillators**: first dubbed as Gliders by Conway, translating oscillators are a type of automata formations that appear to move or “glide” across the grid, increasing their distance from the center of their origin at each time-step.

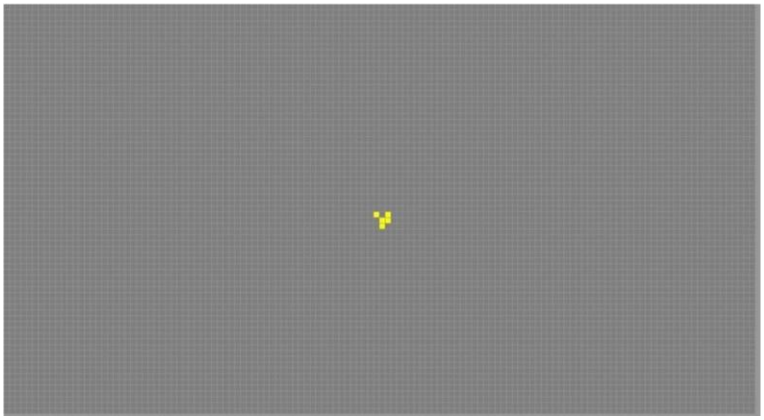


Figure 12a. Glider-starting position

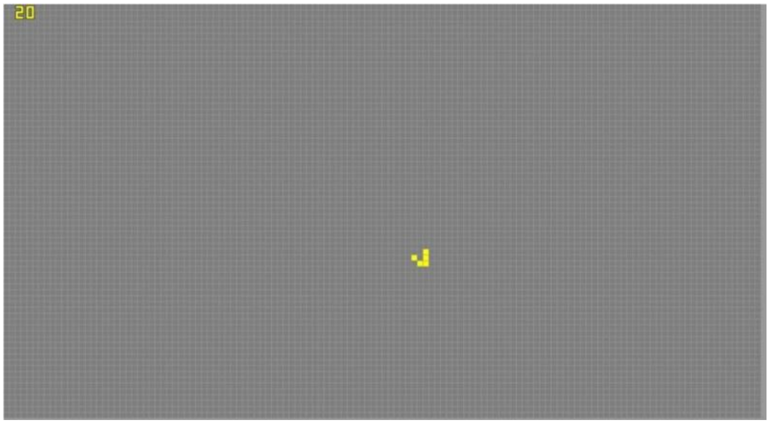


Figure 12b. Glider after one step

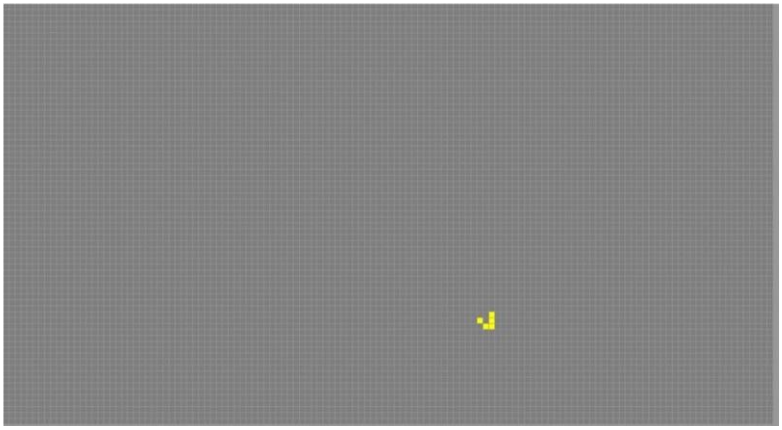


Figure 12c. Glider after two steps

These moving clusters of automata ‘oscillate forever’ (Gardner, 1970; 122) and represents Conway’s most interesting discovery. While the previous two configurations had been previously discovered manually through graphs and boards, it was only after the introduction of CA computer simulations running the game of

> life in the background automatically that these new patterns could surface and be analyzed in detail for the first time. They showed a type of behavior which was initially unexpected and beyond the predictable regularities displayed by the first two configurations. Another characteristic of Gliders is their translating property, as shown by Bays (2010; 3), which is represented by their ability to repeat their pattern after a period of four generations.

So far we have observed the basic components for Conway’s two-dimensional simulation of Cellular Automata. These are represented by the recursive rules applied at every generation, the number of possible states of the automata and the space-time field represented by a two-dimensional grid extending in all directions. Owens and Stepney indicate how ‘that behaviour is known to be very sensitive to a change in the CA rules (2008; 1).The final crucial element to be added lies in establishing the starting conditions for the simulation. More specifically, the initial conditions are represented by the number and position of active cells that will constitute the first generation of automata. In conjunction with the rules that will be enforced during the simulation, the number of active/inactive cells and where the active cells will be initially positioned will determine whether the type of evolution, if any, of the system. For example, the simulation can present a single initial cluster of active cells or several clusters localized at different coordinates on the grid. Adding or detracting single cells can significantly affect the evolution of the cluster by making it vanish or contributing to the formation of complex and long-lived structures. Finally, multiple different initial configurations can converge towards one of the categories described above, eventually becoming oscillators, still lifes or translating oscillators. Factors such as the number of generations needed in order to coalesce into a stable pattern and the coordinates on the grid where this will occur are linked to the chosen initial configuration. Gardner (1983; 246) describes the example of a long-lived still-life type of formation known as Methuselah, and indicates how generally initial clusters containing fewer than ten live cells will require more than fifty generations before they stabilize into static patterns. Conway’s R-pentomino, for example, takes 1103 generations before finalizing its shape. Similarly, in Stephen Silver’s *Life Lexicon* (2006), Methuselah patterns are described discovered by Corderman (acorn) and Trevorrow (rabbits) which also require more than 50 generations before stabilizing.

3.2 Cellular Automata as a nonlinear dynamical system

In the previous section we have discussed the general properties of Cellular Automata and some of the possible configurations and behaviour they can assume when obeying to the rule employed by Conway in the *Game of Life*. While an attempt to provide a general classification of the patterns Cellular Automata may display and evolve into is possible, Hoesktra, Kroc and Sloot (2010; 8) remind that 'it is a known fact that the behaviour of cellular automata is in general unpredictable'. This is further confirmed by Wolfram (2003) as he explains how it becomes computationally and mathematically impossible to devise algorithms which can predict the future evolution of Cellular Automata. This is true of a wide number of rules and initial configurations observed in CA simulations. In short, it would not be not possible to design a shortcut that will reveal the future behaviour of a cluster of Cellular Automata and shed light on what their configuration after an 'n' number of time transitions will be before the start of the simulation or at any point during the simulation. This property marks a distinct difference between programs simulating Cellular Automata and general programs and applications which carry significantly more complex design and architectures in order to perform tasks on modern computers. At the heart of this difference lies the nonlinear nature of Cellular Automata, and therefore the impossibility of making the a priori predictions which instead apply to linear systems including video game applications.

3.2.1 *Differences between nonlinear Cellular Automata and linear game simulations*

Indeed, a comparison with the simulation architecture of game titles, which may often appear highly complex, becomes necessary if we are to understand not only the nonlinear nature of Cellular Automata, but also other ways in which game and CA simulations diverge, which similarities they bear, and how they can be integrated with or complement each other. This final point becomes of paramount importance in the light of our search for a non-deterministic narrative architecture in video games, and will lead to a model for combining Cellular Automata in video games by injecting their distinct properties as a lowlevel component layer in the higher game-AI architecture. As has just been mentioned, a superficial comparison between the patterns displayed by Cellular Automata with the often realistic virtual worlds and characters of modern but also less modern game titles may induce a viewer to consider the latter a more advanced and sophisticated form of the former. As with the *Game of Life*, the internal structure of video games is also designed to respond to several recursive, albeit more complex, classes of rules defined by a hierarchy of initial programming codes and algorithms that will govern the in-game dynamics. Indeed, the short number of rules in Conway's simulation, which can be contained in less than a dozen lines, can initially appear to be an extreme simplification of, for example, the three million lines of code which, according to Creative Assembly designer James Russell (2012), constitute the recent historical strategy simulator *Rome: Total War 2*. Nevertheless, striking though the difference in coding complexity may at first appear, it must be noted that, while in Cellular Automata simulations the code dictates exclusively the rules of interaction between automata, with the rest of the simulation being an automated process driven by an internal clock, a substantial part of the programming in game titles is dedicated primarily to the creation of an interface attractive to users rather than to the algorithm underlying the narrative structure. Central to these are the instructions regarding the interactivity of ingame units with each other, with the game world and, most importantly, with the players.

From the designer's perspective, one of the ways to maximize entertainment is to create a rich and diverse interactive experience for the players, both in terms of how they can intervene in and modify the game world, and regarding what they can observe on the screen. Following this approach, the different types of in-game AI-controlled units, individually modeled as Finite State Machines, can be provided with a large number of states, with the transition from one state to another being governed by specific lines of instructions. These instructions will determine the unit's automated state transitions in the absence of external input as well as their transitions to the several different states which can be caused by events in the game and by the player's direct intervention. Therefore, it is easy to imagine how large numbers of lines of code can be added for one single unit and be part of a higher hierarchy of complex algorithms controlling the general behaviour of the entire game world and its responses to the player's actions and decisions. Factors such as reducing repetitiveness and increasing response diversity are thus central to the complexity observed in game simulations and represent a distinct difference with the non-interactive nature of Cellular Automata.

Yet, as mentioned above, this complexity of initial rules and conditions found in sophisticated simulations such as video games is but a consequence of the logical engineering approach in which, in order to generate complex end products, building tools and instructions of a higher or equal complexity become necessary. Nevertheless, the complexity observed in game simulation, as will become clear later, is primarily of a quantitative nature, with several layers of possible behaviours displayed by game units being added in a highly controlled environment. Indeed, it is the very factor of controllability, guiding the need for designers to provide players with a linear game environment that appears reasonable and meaningful, and that responds logically to external input, that marks the principal difference when compared to Cellular Automata. This factor creates the complex algorithmic infrastructure at the basis of game (and other types of) simulations and gives rise to a close-ended and self-contained game environment which may be diverse but, at the same time, devoid of any unpredictable, independent unit behaviour. On the other hand, Cellular Automata are capable of displaying a qualitative type of complex and unpredictable behaviour. This is due primarily to their nonlinear nature and seems to be a direct result of the very simplicity of rules set at the beginning.

While complex game simulations aim at imitating aspects of reality, thus providing a "screenshot" of nature, Cellular Automata systems are capable of a type of complexity that, as often indicated by Wolfram (2002, 2003) but also generally accepted in the related field of Cellular Automata studies (Fuster-Sabater&Guia-Martinez, 2007; Steeb, 2001; Gros, 2011), can provide a model of how nature creates complexity. This process appears to be generated by simple rules governing an evolutionary architecture which is nonlinear and cannot be predicted.

When we look at complex simulators among video game titles, for example RTS (real time strategy) titles such as *Total War: Rome II* or the latest life simulation offered by *Sims 3* (The Sims Studio, 2009), it is possible to observe how they possess a number of similarities with the Cellular Automata simulations like the *Game of Life*. Initial rules and conditions must be chosen before the game starts, and players' will be able to witness the development, actions and behaviour of their created characters or army which will depend on the parameters established beforehand by the players. Indeed, the general dynamical arc of birth, survival, death or persistence generated by Cellular Automata simulation also applies to the life simulator offered by the *Sims*. Synthetic agents, which are but a sophisticated three-dimensional incarnation of a simple one-dimensional automaton bearing a higher number of possible states and transition rules, represented in this case by virtual humans, are also subject to a number of initial parameters that will determine their birth, type of development and chances of success/failure or survival/death.

As with Cellular Automata simulations, the creation of the laws governing the dynamics of the principal characters in the *Sims* are also paralleled by the addition of a spatial dimension that can be set up at the beginning and which will represent the main stage in which the simulation will take place. After selecting a piece of land in a randomly generated neighbourhood belonging to a virtual city, town or village, players can take advantage of a multi-optional 3-D editor to determine the properties of the immediate environment in which their Sims will be born. This involves different architectural layers and levels of construction roughly inspired by the real-world counterpart, from the morphology of the terrain upon which to build a housing structure, to the selection of large and small details that will constitute the furniture and elements of the final house. During this process, players start by selecting the dimensions and type of terrain and perform terraforming or levelling operations according to their preference. The building of the main house, with its several floors, backyard and front garden ensues, followed by the definition of the various rooms, setting of the main utilities and the final decorative touches to the internal environment. Another similarity to Cellular Automata simulations is also represented by the presence in the game of an internal clock which determines the growth and development of the several agents and entities in the game world. Designed as to represent an accelerated version of the passing of time in real life, the internal clock is generally modelled around the minute/hour, day/week and month/year system, with corresponding daylight and seasonal cycles in order to add a realistic touch to the simulation. Once initiated at the start of each game, the clock cannot be reversed, and, similarly to Cellular Automata, features several "speeds" according to the user's preference or the possibility to pause the simulation and thus freeze the screen at any given time should any modifications or external input be required.

Major differences, however, can be found in the large numbers of initial variables players need to establish for example when creating their Sim, which are supposed to determine his or her development and interactions with other Sims or the game world in general. As has been described in chapter 1, players are given a large range of customization options when creating their Sim. These regard primarily the possibility of choosing biological and physical features, personality and psychological traits as well as aesthetic/accessorial preferences. Physical and biological features include gender and age, body type and a large range of physical characteristics, while personality traits allow players to choose a combination of characteristics from sixty-three traits such as absent-minded, hard-working, artistic and so on. Several points can be assigned to each trait so as to create a complex personality which, along with the physical and biological features, will determine the desires, life-style and chances of survival for the virtual Sim during the simulation. These traits can also be passed genetically to subsequent generations.

When compared to the simple two-state nature of Cellular Automata, it is easy to perceive a picture of greater initial complexity when looking at the *Sims*. Yet the complexity of the initial conditions in the *Sims* does not necessarily lead to the same degree of complexity and unpredictability in Cellular Automata with far simpler initial conditions. This is due to the fact that the *Sims*, as well as video games in general, are deterministic linear systems, where modifications to initial conditions lead to proportional changes during the simulation. Furthermore, single game units are designed as finite state machines operating in a closeended and controlled environment designed to inhibit unpredictable outcomes and favour results that are reasonable or meaningful from the player’s point of view. The system linearity marks the principal divergence between game simulations and simple Cellular Automata simulations such as the *Game of Life*. Indeed, due to the linearity and deterministic logics, by knowing the initial parameters established for a given Sim, it is possible to calculate a shortcut which can reveal all the stages, outcomes and types of behaviour displayed by a Sim at any given time without the need to run the simulation to see what happens. As a matter of fact, save files allowing players to return to a specific point during the simulation operate under the principle of predictability of deterministic systems.

In the *Game of Life*, instead, we are presented with a basic two dimensional grid with simple one dimensional pixels that can be either blank or filled. A very limited number of rules (three in Conway's case) are set which determine the development and interactions of the automata as they unfold from generation to generation through a simple internal clock setting the pace of the simulation. It is the initial simplicity of rules and conditions which, in opposition to the simulation described above, is capable of generating complex organizational behaviour driven by a nonlinear evolutionary dynamics. Therefore, running the simulation and performing continuous observations during the life-cycle of Cellular Automata remains the only valid method to analyze their behaviour and structures, and this is particularly true for simulations where the spatial grid is non-finite and extends indefinitely for as long as there is cellular automaton activity. Only after a specific initial configuration has run its course it will be possible to trace and model the dynamical evolution of Cellular Automata, as well as state that the simulation will provide identical outcomes in the presence of the following:

1) Identical initial conditions

These regard the number of initial live cells and their exact starting position on the grid. Any small addition or subtraction to the initial cluster of cells would generate entirely different results. Similarly, adding live cells to different locations on the grid seemingly unrelated to the principal cluster may, in some cases, cause significant changes to the overall dynamical behaviour of the automata. Finally, in grids having both finite and nonfinite configurations, the shape and geometry must also remain unchanged if we are to achieve identical results for a particular simulation.

2) Identical recursive rules and neighbourhood type

Obvious though it may appear, an essential condition is to ensure that the same initial rules are enforced during the simulation and that they will apply recursively at every generational step. The same applies to the type of neighbourhood (Von Neumann or Moore's) established. Also in this case, slight changes to the laws governing the neighbourhood, and therefore to the number of cells in the immediate vicinity to interact with, will lead to very different developments and outcomes.

3) Absence of perturbations

As hinted in point 1, absence of perturbations indicates the absence of any form of external input or interference with the system that may occur during the simulation and directly affect the outcomes. Perturbations may therefore be in the form of adding live cells at any point or location during a specific simulation, altering the shape of a finite grid from rectangular to circular or, for example, reversing the time-sequence (Wolfram, 1986; 91). Aside from the frequent effect of destroying entirely the evolving automata clusters, external interference will cause the system to behave in an exponentially different way.

While, as we will see, Cellular Automata can, according to the rule category they belong to, display behaviours ranging from regular and periodic to aperiodic and chaotic and finally extremely complex, they all possess the property of nonlinearity which makes them obey to the above mentioned guidelines for repeatability. Indeed, the conditions discussed above, which are necessary to repeat the results for a specific configuration, essentially tell us that Cellular Automata behave and evolve in a nonlinear manner, and can therefore be considered as nonlinear systems. Lam (1998; 6) indicates that 'a system is nonlinear if the output from the system is not proportional to the input'. Similarly, Hilborn (2000; 3) simplifies the concept: 'kick the system and note its response. Kick it again, twice as hard, and again note its response'. While in a linear dynamical model, the system's response will be proportional to the stimulation applied to it, a nonlinear system will display a nonproportional change which, according to the system in question, will be exponentially or qualitatively different, or both. For example, when employing Conway's rule of *Life*, several randomly generated initial configurations can give rise to travelling clusters of automata or gliders. By identifying, as shown by Gros (2011; 157), any of these initial configurations, we will soon discover that even slight changes made to the initial number of live cells or their position on the grid will not have the same proportional repercussions that we might expect from a linear system. For example, doubling the number of initial live cells will not result in a glider formation containing twice the number of constituents, and indeed may lead to types of patterns rather different than the propagating glider structures, such as stable periodic patterns localized in a finite region or patterns that vanish entirely after an 'n' number of generations (Jost, 2005; 170).

Earlier in this chapter we have seen how Cellular Automata simulations respond to the starting conditions in a way similar to other types of nonlinear systems, and their high sensitivity to the initial input and perturbations in general can give rise to exponentially and qualitatively different results. What this tells us is that Cellular Automata can display chaotic behaviour characteristics of nonlinear systems observed in nature such as the weather. Niemec (2010; 119), for example, indicates how altering the state of a cell during an ongoing simulation can lead to a 'chain of events where a small spark that occurs at one point in time will cause a specific change of one cell elsewhere at a later point in time'. This is also known as the Butterfly Effect and confirms the ability of Cellular Automata simulations with rules such as those in the game of life to offer great evolutionary diversity in the presence of external noise or input.

3.2.2 *Irreversibility and self-similarity*

Further traits observed in nonlinear dynamical systems which emerge in certain configurations of Cellular Automata are represented by the property of irreversibility, selfassembly or fractals, and the presence of attractors determining the system's evolutionary trajectory. Nakamura et al. (1986; 38) indicate how nonlinear dynamical systems showing chaotic behaviour display 'certain kinds of complexity of motion' in which the property known as irreversibility arises. In nonlinear dynamical systems such as the doublependulum, irreversibility coincides with chaotic regions of the phase space (where the trajectory of the system evolves) in which 'the motion of the system becomes erratic' (Nakamura et al, 1986; 39). When these conditions of chaotic and erratic behaviour arise, a system can be said to be not-backwards-deterministic. This leads to an impossibility of reversing the dynamical evolution of the system in order to restore it to its exact initial conditions. In some classes of Cellular Automata it is possible to observe the same property. Both Steeb (2001; 300) and Wolfram (1986; 131) suggest from empirical studies that most Cellular Automata dynamical evolutions are not reversible. Randomly generated initial conditions present maximum entropy where all possible future configurations bear equal probability. Wolfram explains how once the simulation begins, the entropy decreases, resulting in a 'contraction of the set of configurations generated by a cellular automaton' (130). During the evolutionary trajectory, information is lost as the probability of some configurations decreases while increasing for others. In Cellular Automata, this occurs when a configuration does not have one but many possible predecessors, implying that the ‘time evolution mapping is not revertible, but is instead “contractive”‘ (223).

Another feature present in some Cellular Automata configurations which emerges in nonlinear dynamical systems is the fractal property, or self-similarity. According to Wolfram (130), ‘some Cellular Automata give regular and self-similar patterns’.

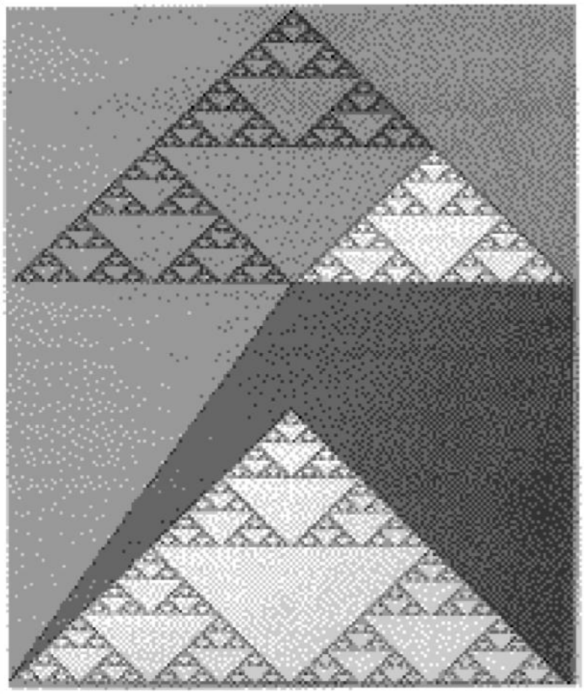


Figure 13. Cellular Automata fractal patterns

In the picture above we can observe an example of self-similarity of structures in Cellular Automata. A small portion of the image, when magnified, becomes indistinguishable from the whole. Lam (1998; 11) explains how the fractal property derives from ‘the selfassembly of a large number of identical components’, and results from the combination of the principles of regularity and randomness and is observed in many nonlinear dynamical systems in nature and in the physical world. Similarly to crystals, Cellular Automata tend to arrange themselves in periodic or quasi-periodic patterns (regularity), and seem to follow the same random principle guiding, for example, the distribution of animal hairs, patterns on animal shells or distribution of molecules in gaseous systems.

The simplicity and experimental accessibility make Cellular Automata ideal tools to study and model complex nonlinear phenomena occurring in the physical world. One particular reason is their discrete nature. As explained above, Cellular Automata are discrete dynamical systems in which all the simulation components such as number of states of the automata, temporal and spatial trajectories as well as initial and transitional rules have a finite nature. To this regard, Hoekstra, Kroc and Sloot (2010; 8) indicate how the discrete nature of Cellular Automata can, for example, be helpful in predicting ‘average, asymptotic and other properties of simulated natural phenomena’. From this perspective, and also thanks to the extensive categorization studies carried by Wolfram (2002), Cellular Automata represent a discrete nonlinear system which is highly controllable. By repeatedly simulating the system through the change of the initial rules and conditions and the other parameters it becomes possible to identify a model and trace the outlines of examples of complex systems in nature, as in Wolfram’s examples of snowflakes and crystal formations. The nonlinear properties of Cellular Automata have indeed enabled their use as a model to study a wide range of nonlinear phenomena. To this regard, Gros (2011; 156-177) demonstrates how the simple model of Conway’s simulation can be used to analyze nonlinear complex phenomena such as forest fire, avalanche, sandpile criticality and species evolution.

3.3 Cellular Automata Classes and Evolution

So far we have discussed the historical background and development of Cellular Automata as mathematical and computational models and have highlighted their characteristics as a discrete nonlinear dynamical system. The focus has been principally on the rules employed in Conway’s *Game of Life,* primarily due to the interesting behaviour and patterns these have been observed to generate. Following these simple rules that not only attempt ‘to simulate the reproductive cycle of a species’ (Gros, 2011; 156), but follow the fundamental laws of natural evolution and survival, it has been possible to identify three general categories in regards to the types of dynamical behaviour displayed by the automata. These are represented by still lifes, oscillators and translating oscillators, and we have seen how each configuration will eventually evolve into one of these categories after a number of generations according to the starting initial conditions.

However, in the tracing of the evolutionary model of Cellular Automata, Wolfram's extensive analysis and empirical studies have produced a classification of four distinct evolutionary categories differentiated according to the type of behaviour displayed. This more detailed classification results by applying not only Conway's rules, but all the possible sets of initial rules. According to Li and Packard (1990; 281), 'a cellular automaton rule is represented by…a list of state values to which block configurations are mapped'. Therefore, simulations in which Cellular Automata possess a number of two states (on/off) will operate according to a maximum of 256 possible rules which will govern the interactions and state transitions of the automata. Wolfram's (1984; 1-35) four category classification results from enforcing all 256 on randomly generated automata configuration, and therefore represents the most complete model. Below is an explanation of the 4 classes mapping the evolution of Cellular Automata.

Class 1

In this category, the evolution of Cellular Automata is finite. After a discrete number of generations, the automata reach a homogeneous state, where all sites have the same value (either on or off). In this scenario, 'the evolution completely destroys any information of the initial state' (Wolfram, 1984; 22). In short, all initial patterns disappear.

Class 2

Cellular Automata belonging to this category do not disappear, but reach a stable or periodic localized state, where the initial pattern is conserved in a finite region of space (Jost, 2005; 170). Most applied rules lead to stable persistent structures, while in other cases small periods can be observed.

Class 3

The regularity of the first two categories is replaced by chaotic and aperiodic behaviours displayed by class 3 Cellular Automata. In this class initial clusters of Cellular Automata travel across the grid and continue to grow indefinitely (unbounded growth) into wider regions of space without stabilizing into periodic or static patterns. In this case it is possible to observe how the majority of initial configurations lead to the formation of fractals, or self-similar patterns, often of triangular shapes, where their form 'is identical when viewed at different magnification [scales]' (Wolfram, 1984; 25). Other possible evolutionary outcomes include the appearance of growing shapes presenting no regularity and no largescale structures. In this class two interesting features have been highlighted. The first is represented by the ability of Cellular Automata to display a frequent tendency to selforganization even with disordered initial conditions. The second property comes from a high sensitivity to initial conditions can be identified, described by Wolfram as 'instability' (1986; 514). Small changes to the initial conditions will lead to marked differences in the evolution of the system analogous to the exponential change rate of nonlinear dynamical systems.

Class 4

This is where the most complex Cellular Automata behaviour can be observed. Jost (2005; 170) describes how 'the evolution leads to complex, spatially localized patterns that grow and shrink in a regular manner and can propagate in a solition-like manner'. A major difference with the other categories is the presence of propagating structures, as observed in the glider gun of the *Game of Life,* which is included in this class. The glider gun generates 'an infinite sequence of propagating structures' (Wolfram, 1984; 31) in a background characterized by cyclic expanding and contracting patterns. One rule in particular, rule 110, contains several types of gliders or propagating structures, self-replicating fractal patterns and has also been shown (Cook, 2000) to satisfy the conditions for being computationally universal, or Turing complete. The latter property is based on the assumption that the system is capable of producing every possible algorithm, can display complex behaviour and 'even if the initial state is completely known, the longtime behaviour can only be found by explicit application of the dynamics' (Jost, 2005; 170). In the light of all the complex elements contained in this category, for which 'no meaningful prediction is therefore possible for such systems'

(Wolfram, 1984; 35), the rule model represented by class 4 Cellular Automata represents the most promising approach to address the deterministic nature of video games.

3.4 Examples of Cellular Automata models

So far we have discussed the nature of Cellular Automata in terms of their structure and mechanics. We have seen how simple rules can generate complex evolutionary outcomes and how slight variations can lead to significantly different results during Cellular Automata simulations. Through the application of different initial rules and starting conditions it becomes possible to distinguish, along general lines, groups of configurations such as still lifes, oscillators and translating oscillators, and also the four specific categories of Cellular Automata identified by Wolfram's extensive experimentations, each one of them bearing distinct properties and obeying to regular developmental patterns. Through the interaction of individual two-state automata by means of recursively applied simple rules in a discrete time-unit progression, it is possible to witness complex phenomena such as self-organization, preservation and longevity. As indicated by Lam (1998; 11), Cellular Automata simulations can also generate complex structures which are results of their single components assembling themselves in fractal formations and bearing the property of selfsimilarity, thus resembling similar systems found in nature. Finally, it has been asserted how the dynamical mechanics observed in the evolution of Cellular Automata enables us to identify them as nonlinear dynamical systems. Fundamental properties of nonlinear dynamical systems such as simple-to-complex evolutionary development, nonpredictability of simulation outcomes and presence of attractors determining evolutionary trajectories are also found to operate during Cellular Automata simulations. Furthermore, subtle changes to the starting conditions and the presence of perturbations greatly affect the outcome of the simulation.

The properties here discussed, which are extensively analyzed by Wolfram (1984, 1986, 2002), Duff and Preston (1984), Hoekstra, Kroc and Sloot (2010), enable us to identify Cellular Automata simulations not only as nonlinear dynamical systems themselves, but also indicate how they can be used as a model to analyze and improve our understanding of the nature of complex and chaotic systems found in the physical world and a range of phenomena observed in biology and society. To this regard, Choudhury et al. (2011; 1) explain how 'CA rules have many real-life applications in almost all areas of science like physics, chemistry, mathematics, biology, engineering and finance'. We have already seen the example provided by Wolfram in which the formation of complex patterns observed in a snowflake can be emulated through CA simulations. This enables us to draw parallels between the simple rules enforced in CA simulations and their hypothetical counterpart in natural processes occurring in the physical world which may drive the generation of complex patterns from relatively simple initial conditions.

3.4.1 *Cellular Automata as a modelling tool*

Cellular Automata can therefore be used as a modelling tool to represent complex systems. Before identifying the role they may play in an Artificial Intelligence environment in video game design, and how they may provide the fundamental architecture for non-deterministic unit behaviour to emerge, we will first look at some examples of their use as models in other fields of applications. It is, however, important to first clarify that the method of using Cellular Automata as a model to emulate, replicate and generally understand various phenomena is indeed in opposition with the model proposed in this study for the application in game design. Whereas Cellular Automata are being used as a simplified model of phenomena such as, for example, population growth dynamics, in video game design the objective is to extract the principles and basic rules found in abstract Cellular Automata simulations such as Conway's *Game of Life*, and introduce them in an AI environment where they can be programmed to drive the behaviour, development and evolutionary dynamics of foreground and/or background game entities.

Johnston indicates how, in the light on Conway's contributions and the increasing accessibility of computing systems, the idea consolidated of Cellular Automata as revealing entities to understand complex systems. During an interdisciplinary workshop at Los Alamos National Laboratory in 1983, Wolfram explained how the discrete nature of Cellular Automata and their ability of parallel rather than serial processing 'is found in many natural systems' (1983; vii-viii). According to Johnston, this 'could provide a new and better tool for studying the behaviour of complex dynamical systems' (2008; 170).

3.4.2 *Particle dynamics*

The modelling of various phenomena employing Cellular Automata started to be seen as an additional method of scientific inquiry made possible by the advent of computation. Hoekstra, Kroc and Sloot (2010; 1) refer to this as ‘a third scientific paradigm’, namely ‘the computational paradigm, in which we study Nature through computer simulations’. A large variety exists of simulations which take advantage of increasing processing powers to recreate a wide of phenomena, from the birth and development of our Universe, formation of galaxies and planetary/star systems, to the modelling of nuclei and electron orbital paths at the atomic level. Cellular Automata represent one specific type of computer simulation among many, and also require less processing power due to the inherent simplicity in their initial conditions and overall organization of the simulation. The several levels and forms of complexity illustrated previously in this chapter render them suitable tools for understanding equally complex phenomena observed in nature, such as flocking and/or group dynamics in the animal world, autonomous formation of fractals and complex patterns observed in geology and ecology and vegetation dynamics as in Balzter, Braun and Koehler (1998; 113-125) and Benenson and Torrens (2004).

Furthermore, another advantage of using CA models to understand natural systems is introduced by Toffoli and Margolus (1987; 141) as the ability to observe and understand the dynamics of a system without disturbing it directly. Particle dynamics is one such domain, in which CA models can be employed and properly configured so as to understand the behaviour and interactions of particles travelling in different types of medium such as vacuum or fluids as well as coalescing in gaseous systems. Toffoli and Margolus (164) describe one such experiment conducted by Califano, in which Cellular Automata are modelled so as to represent the dynamics resulting from the paths and collision of gas particles. Single Cellular Automata represent individual gas particle, and their path is determined by a discrete number of steps, with their initial and final positions being recorded. As explained, ‘each run entails...simulating the entire gas system, consisting of tens of thousands of particles’ (Toffoli and Margolus, 1987; 164). The CA configuration consisted of a rotating two-dimensional grid, with single automata moving across the grid from left to right according to one single rule whereby if the collision condition was “true”, the automaton would stay on the current square until the next time step. If the collision condition was “false”, the automaton would proceed to the next square. Since the ‘entire history of a thousand-step simulation can unequivocally be compressed into a string of a thousand bit’ (164) it is easy to see how even simple 8-bit processors could calculate the paths and collision of multiple automata simultaneously. By employing Cellular Automata, Califano was able to simulate a simplified model of the complex interactions of particles in a gas medium, and was eventually able to determine numerical values for the probability distribution of such particles.

3.4.3 ***Gas diffusion, wave and fluid dynamics***

A similar type of CA configuration, known as TM-GAS (Toffoli and Margolus, 1987; 119) was also used to analyze the dynamics of gas diffusion within a container. This configuration is designed specifically to analyze particle collisions, and is based on the Margolus Neighbourhood (119). It consists of a finite grid containing several independent units or blocks made of four squares, each of which can be populated by an automaton. The condition of each block is updated at every step and, according to the needs of the experiment, these blocks can be made to overlap at every step. Toffoli and Margolus explain how this type of CA configuration can be used as a model for particle dynamics in both non-interactive uniform motion and colliding scenarios. Particles populating each block can travel in four possible directions horizontally and/or vertically. With the overlapping of blocks at every step, they may collide with other particles, and their new direction will be determined by the particular angle at which the collision took place. In the case of gas diffusion in a container, collision will also be caused by particles bouncing against the edges of the grid. During experiments simulation particle diffusion, they noted how, while a single automaton will travel ‘in a jerky fashion, describing a tangled, unpredictable path’, when looking at the collective behaviour of all the automata on the screen, ‘a dense cluster of particles will slowly diffuse in all directions’ (157). Furthermore, they noted how particles tend to move in straight lines towards the walls, bounce and disrupt the path of other particles, and eventually reach a ‘state of thermodynamic equilibrium’ (160) with the initial cluster of particles becoming uniformly diffused throughout the available space of the grid.

Cellular Automata models simulating the motion of particles coalescing into gas clouds are also frequently used to represent an idealized version of the motions and behaviour of waves moving as a fluid, as in experiments conducted by Salem and Wolfram (1986) and D' Humieres, Lallemand and Shimomura (1985). They both recreated the behaviour of hydrodynamic flows while passing an obstacle. Also in this case, the basic configuration consisted of individual particles constantly moving in the four possible directions across the grid. In order to promote the global direction of a swarm of particles towards a specific direction, and therefore initiate the flow, more particles were added to the automata following a chosen trajectory. After generating the hydrodynamic flows, obstacles would be added in arbitrary locations on the grid in the form of additional layers which would reflect the particles and force a detour.

3.4.4 *A-Life and population growth*

A wide domain in which Cellular Automata are employed as models is represented by life itself, its complexity and the dynamics of its evolution. More specifically, Johnston (2008; 167) indicates how the self-organizational behaviour observed in computed Cellular Automata simulations, based on the self-replicating capabilities initially formulated by Von Neumann, represent one promising prospect for the future of Artificial Life. He explains how observations made on Cellular Automata have challenged the traditional idea of machines as lacking 'purposiveness, or the capacity to be self-organizing and self-directed' (167). Therefore, in the light of the complex behaviour observed not only among inanimate systems in nature, but more importantly in a simulated and artificial environment, 'when machines begin to self-organize and reproduce, they attain a dramatic kind of "life" never before imagined' (167). Cellular Automata represent a type of abstract machine capable of reproduction and seemingly purposeful behaviour, and can be included in Maturana and Varela's notion of Autopoiesis, which identifies living systems as 'autonomous entities...endowed with the capacity to reproduce' (1972; 73). Also when applied to nonbiological organisms, the notion of autopoiesis sees machines as equally complex living systems if they are 'organized as a network of processes of production of components which, through their interactions and transformations continuously regenerate and realize the network of processes that produced them' (1972; 78-79). Von Neumann's selfreplicating automata and the gliders resulting from the *Game of Life* are complex systems whose evolution is determined by the interaction of the single automata among themselves and guided by the initial rules. This interaction leads to a self-organized system which reproduces itself and maintains a constant equilibrium.

Another prolific area of application of Cellular Automata is represented by studies analyzing population growth dynamics as observed among a wide range of living organisms from virus and bacteria to humans. Comprehensive examples of coupling population growth observational data with Cellular Automata models so as to analyze patterns underlying the growth and spread process are presented by Jafelice and Da Silva (2011). They discuss two types of population evolution as observed at the macro scale in Edelstein-Keshet (1988) and Renning's experiments (2000) of shark-preys dynamics and at the micro scale regarding the evolution of HIV virus in the presence and absence of antiretroviral therapies. A key factor to observe in these tests is the spatial distribution of the subjects, represented on a modelled scale by the automata and their trajectories on the grid. By implementing a basic CA simulation where single cells possess two possible states whose transition is determined by the interaction with the neighbours according to initial rules imitating 'biological and physical laws that guide the system behavior' (Jafelice&daSilva, 2011; 105), the complexity shown by the systems analyzed is re-created, along general lines, through the behaviour of Cellular Automata. The predator-prey dynamics were simulated by a two-dimensional CA employing a Moore neighbourhood in order to understand 'what causes the changes in reproduction and survival' (106). Additional elements were integrated to determine the evolution of the single automaton representing a fish or a shark in the form of 1. fish reproductive age, 2. shark reproductive age and 3. sharks starvation period. By taking advantage of the graphical elements of CA, and therefore the possibility of carefully studying movements and trajectories, several simulations contributed to demonstrating 'the crucial role of spatial inhomogeneity into the dynamics of biological species' (110).

In the case of HIV infection dynamics, a CA model was devised representing the three main stages of the illness such as initial infection, asymptomatic and symptomatic phases (112). The automata were divided into uninfected, infected and free virus particles. The interaction between free virus particles with uninfected cells would therefore generate infected cells, providing insights into the replication rate and dynamics of the virus. Again, elements such as life span limits of cells and antibodies were added. By looking at the simulation on screen, Jafelice&daSilva describe how the simulation shows how each free HIV virus particle initially ‘searches for uninfected cells...in its neighbourhood’ (116). An uninfected cell is therefore chosen randomly by the virus and becomes infected. If the virus can’t find uninfected cells in its neighbourhood, it stays there until it ages and dies. Infected cells replicate after a specified number of time-steps. Similar dynamics apply to antibody particles seeking and destroying any infected cells in their neighbourhood. In the antiretroviral therapy scenario, an additional element appears in the form of ‘fuzzy rulebased systems’ (119) which introduce a probabilistic component representing the diversity of physical response among individuals to antiretroviral drugs. Final observations indicated how CA models manage to approximate ‘the trajectories of all phases of the HIV history’ (126), and this goes beyond traditional models which emphasize only initial infection phase.

3.4.5 *Traffic dynamics*

Aside from life itself, evolution and its dynamics, as well as complex phenomena in the natural world at the macro scale or at the quantum level, there are also other pockets of complexity and chaotic systems emerging from and observable in several domains of human society which can be analyzed through Cellular Automata models. As with the examples explored above, the interactions of single Cellular Automata through defined initial rules can give rise to macroscopic phenomena which are not displayed by the individual constituents of a system by arise as a collective behaviour. For example, Maerivoet and De Moor (2005; 1-64) employ a customized CA configuration known as Traffic Cellular Automata (2005; 2) in order to generate a ‘vehicular traffic flow modelling’ (2005; 3) and therefore study the dynamics of road traffic. Similar to Cellular Automata simulation layouts previously discussed, Maerivoet and De Moor’s model consists of a flat grid of squared cells, which represents ‘the road on which the vehicles are driving’ (7) and can be either open (bottleneck scenario) or closed (Indianapolis scenario) according to the type of traffic flow dynamics under investigation. This two-dimensional map is populated with one dimensional automata which can transition into two possible states (on/off) and therefore fill the cells of the grid or leave them blank. Once the simulation is initiated, the familiar evolutionary process ensues, determined by a discrete time-step development and guided by two factors: the neighbourhood type and a local transition rule. These two elements are inter-connected as the rule for determining the trajectory and survival/death of each generation of automata will be expressed through the interaction between a given automaton with its neighbours. These factors, namely the physical environment, the cells' states, the cells' neighbourhoods and the local transition rule (6) are established prior to the start of the simulation and represent the initial conditions that are crucial to the emergence of complex dynamics afterwards. Once started, the simulation will proceed independent of external input, through a discrete time model in which the local transition rule will apply at each step.

For the model to recreate the complex dynamics observed in traffic flow, Maerivot and De Moor emphasize how the principal objective is to reach 'self-organisation', namely a 'global complex behaviour' emerging from 'local simple interactions' (7). The complexity of real life traffic dynamics which, for example, can be observed in an urban setting from an elevated viewpoint is the result of individual elements, in this case the car-driver unit, interacting with their neighbours, other car-driver units through pre-established rules dictated by the traffic law, which also include environmental elements such as pedestrian stripes, traffic lights and so on. Aside from replicating these elements and the ensuing complex patterns, Cellular Automata models, as a nonlinear dynamical system, also present points of attraction guiding the moving automata towards certain areas on the map. These can be used to analyze attractors of traffic flow. The efficacy of 'the cellular automaton analogy to vehicular road traffic (7) also suggests the applicability of Cellular Automata mechanics in game design and particularly regarding automated dynamical systems. Indeed, when discussing how to employ the mechanics of Cellular Automata in game design, we will see how certain types of simulations might particularly benefit from this approach. For example, applying Cellular Automata mechanics to resource management and real-time strategy games like *SimCity*, *Spore* or *The Sims*, in which players control the development and evolution of entire cities, large-scale environments and populations, would not only automatize processes whose behaviour is traditionally built by following FSA models and large numbers of (sometimes) complex algorithms, but would also add complexity and diversity for a non-deterministic unfolding of background events.

Chapter 4. Integrating Cellular Automata in the Game AI Architecture

4.1 Deterministic and Nondeterministic Game AI

Before considering how the principles of nondeterministic complex systems, and Cellular Automata more particularly, can be incorporated into game narratives in particular, it is important to understand the traditional, and less traditional, AI techniques currently used in game design. The importance of this lies in the fact that using a basic Cellular Automata configuration in game design so as to affect specific background or foreground game entities it is only made possible by integrating it within the game's built-in AI architecture.

By looking at AI structures currently employed, it will be possible to see how the largely deterministic AI game methods are, in certain cases, accompanied by nondeterministic techniques which inject controlled amounts of probability in order to diversify the behaviour or NPCs and game worlds. However, it must be clarified that, while AI programmers normally refer to these techniques as nondeterministic, such methods do not generate true emergent and complex behaviours such as those, for example, observed in Cellular Automata, but only reduce the amount of repetitiveness in games which are largely driven by deterministic and pre-established scenarios with finite sets of outcomes. Nevertheless, we will see how some of these techniques, namely Artificial Neural Networks and genetic algorithms, could prove fruitful if exploited in games designed around principles governing the behaviour of nonlinear complex systems.

So what does the AI actually do in the game? We have said that it controls the entire behaviour of NPCs, the game world and its dynamics. A major distinction, useful for the purposes of this study, can be made between deterministic and pseudo-nondeterministic (probabilistic) AI methods. According to Millington (2006), deterministic AI techniques lead to in-game behaviours of NPCs and game environments that are specified, controlled and predictable. Most of AI techniques used in games adopt this category in order to avoid, for example, uncertain NPC behaviour which might jeopardize the gameplay experience. Deterministic techniques may give full control to the designers over what happens in the game, and the gameplay experience can be accurately crafted so as to maximize entertainment. However, as Bourg and Seeman note, one major drawback is having to anticipate 'all scenarios and coding all behaviours explicitly' (2004; 24), and in addition multiple gameplay sessions will eventually lead to repetition, as already mentioned. In pseudo-nondeterministic approaches promoting probability and randomness, however, nonpredictability constitutes an essential feature of NPC behaviour, and the degree of uncertainty will vary according to the degree of unpredictability designers want AI units to have. While still a rarity in game design, attempts have been made at implementing nondeterministic techniques in the form of artificial neural networks and genetic algorithms to enable NPCs to learn and adapt independently, or 'make decisions when the states of the game world are uncertain' (Bourg&Seeman, 2004; 244) by using Bayesian networks. In our search for emergent behaviour and narrative in computer games, it is easy to understand how nondeterministic techniques represent a most promising direction, since unpredictability and fully autonomous behaviour are essential steps to be taken in order to cause unforeseen series of events. Furthermore, foundations are already being established with methods such as flocking and neural network algorithms that have been shown to be able to promote emergent behaviour.

Regardless of what type of nondeterministic model is being used, the AI in games is normally deployed through a specific number of fields of application. According to the general literature for AI game design, specifically when looking at Champandard (2004), Rabin (2010) and Lecky-Thompson (2008), four broad areas of application can be highlighted as they are present in the majority of video game titles. These areas involve movement, planning, interaction and environment. The degree of complexity of AI methods employed may vary considerably according to game genre, and this will also affect the priority within the same title which may be given to different areas. Furthermore, once the AI is applied to these game components, the consensus among AI game developers is that it needs to be entertaining, challenging and believable. This, according to Champandard, are 'common requirements...to be taken into account when engineering the AI system' (2004, 13). These factors effectively summarize the history of AI applied to the computer game environment, seen, ever since the appearance of the medium, as a set of discrete problems to solve (make characters behave logically, provide a fair challenge, provide helpful NPCs etc…). We have seen how the credibility lies in the attempt to make NPC characters behave as humans or behave logically according to the specific domain or context. In terms of challenge, however, given the obvious advantages that AI units would have compared to the players, a most important factor, also highlighted by Rabin, is that 'opponents must lose to the player in a challenging and fun manner' (2010; 522). This brings us to a frequent technique known as AI "cheating". In games where players face opponents in different types of contexts, as for example in shooters, AI units are given information regarding the player's position and status at all times as, unlike human players, they do not have a sensory system allowing them to "feel" the environment around them. As Rabin reminds us, 'the game world is wholly inside the computer, and the AI has the luxury of performing its analysis on these completely accurate representations' (523). As mentioned earlier, game worlds present a fertile application ground for AI technology since all problems related to teach a synthetic robot to sense the environment are eliminated. This also means that AI units navigate and act in the game world by asking and receiving constant feedback from the game engine.

While cheating provides a solution for the need to overcome limitations as to how intelligent NPCs can be without the same sensory perception possessed by the human opponents, a major effort goes into tweaking their complete knowledge of the game world and penalizing them in order to make them perform on par with the player and make the game playable. In sports games cheating is the most recurring AI technique, as observed for example in driving games. For a given track, the AI controlled cars already know what the optimal trajectory is, and with accurate calculations of position and velocity it would prove impossible to beat them. Reducing the opponents' velocity if these take over the player's car, and forcing longer braking sessions are some of the methods used to adjust what would otherwise be a perfect AI.

4.1.1 *Movement, path-finding and planning AI*

A primary objective for the AI is to guide non-stationary NPCs through the virtual world and dictate their movement. Since the majority of games present challenges through different types of opponents, path-finding AI represents one of the most frequent techniques employed by designers. The objective is for all moving units within the game, whether friendly, enemy or neutral, to navigate through the environment from point A to point B and to avoid any possible obstacles which may halt their movement. In order to facilitate NPC movement, Champandard (2004; 60) explains how game environments are built comprising a double-layered architecture. One layer has a more functional role for the AI, and can be defined as structural. It includes the main physical objects in the space that may represent an obstacle to movement, such as doors, walls, tables, trees, roads and all similar elements scattered across the environment. The second layer, defined as detail, is of a cosmetic nature and includes minor objects that have no impact upon the movement and therefore bear no significance for the AI. Since NPCs have no sensory perception of the space around them, the path-finding AI method enables them to move from checkpoint to checkpoint thanks to the distribution of waypoints along the way. The sum of these waypoints are known as 'terrain model' (Champandard, 2004; 73), and NPCs navigation across the terrain occurs by means of the AI path-finding or search algorithm known as A* that will calculate the shortest path between two checkpoints. Charles et al. (2008) explain how the A* search algorithm is one of the most used AI technique, as its utility extends beyond unit movement as 'an attempt to find a solution in some more abstract problem space' (6). The usefulness of the A* algorithm comes from its reliance on a heuristic search method, employed to 'choose branches in a state space that are most likely to lead to an acceptable problem solution' (Luger, 2009; 123). Concerning path-finding, heuristics are used in order to calculate the approximate distance between two waypoints and from the initial point to the final destination. This removes the need for breadth-first and depth-first searches, which in complex cases may require excessive usage of CPU cycles and long durations which may break gameplay.

Alternatively or in combination with pre-established waypoints, Millington (2006) describes another technique known as Breadcrumb Path-finding, that looks directly at the traces left by the human player and moves NPCs along them. The path-finding method by means of A* algorithm is particularly successful for static environments where obstacles have a fixed position and the AI provides NPCs with a pre-processed complete knowledge of the terrain. However, problems arise with dynamic environments whose terrain properties change continuously. A number of obstacle avoidance algorithms are in this case implemented in the form, for example, of a 'virtual volume that extends out in front of the unit' (Millington, 2006), also known as 'radar style' (Lecky-Thompson, 2008; 38) used to test the geometry of the virtual space and predict possible collisions in the vicinity of obstacles. This subjects the NPC to a steering force that guesses the closest free space and moves the unit accordingly. Path-finding and unit locomotion are often seen as the execution of the low-level AI layer that is directly controlled by a higher-level decisional AI that selects which objectives NPC units need to achieve and which strategy they are advised to follow. The combination of low and high level instructions is understood as planning AI, and is most apparent in RTS (Real Time Strategy) games, where the AI controls a large number of units both singularly and as a group, and, for example, in football simulations, in which the NPCs actions and movements are determined by the strategy selected to reach the pre-established objective. One of the successfully implemented planning AI methods relies on the STRIPS planning algorithm developed by Fikes and Nillsson in 1971, in which an initial state and a final state or goal are defined. A set of actions represents the intermediate state that determines what type of strategy and subsequent actions NPCs will take according to whether certain conditions are met. The types of action will normally depend on the player's own status and actions.

Finally, an intermediate AI layer between high and low level can be identified and is described by Lecky-Thompson as medium-level AI (2008; 31). This layer handles the interactions of NPC units among themselves and with the player. Considering that one of the core elements of game design (and a major appeal) lies in the interactivity, it is understandable that not only more efforts are channelled towards NPCs interactive behaviours, but also this is where more sophisticated AI structures are found. As discussed before, a commonly used AI method to script behaviours and interactions is known as finite state machines, which guide the behaviour of NPCs and the transitions between each behaviour. Rabin defines finite state machines as ‘an abstract model of computation that consists of a set of states, a starting state, an input vocabulary, and a transition function that maps inputs and current states to a next state’ (2010; 530). Any element in the game world, whether NPCs or objects, possesses a defined number of states and will transition among them during gameplay. We have seen how these states may take a wide variety of forms: an enemy unit may be in a patrol, rest, attack or retreat state, and according to which state is active at a particular moment, the objects or NPCs will respond, and therefore interact, in a particular way to external stimuli or user input. Each type of action and transition are coded through if/then or true/false script protocols that define the conditions to be met. The FSM models used in game AI derive from abstract models known as Moore and Mealy machines, which differ according to whether the machine performs actions during the transitions or when stationary in a given state. In game development, units perform actions both during a given state and during a transition, and in order to make interactions more varied, randomness and probability can also be added. A patrolling soldier, for example, may have a 10% probability of fleeing if detecting the player, 70% of attacking and 20% of calling for reinforcement. Each state can be considered as a behaviour node, and the input from the user or from other NPCs or events in the game world will initiate the transitions to other states. A semi-deterministic extension of FSM is known of Fuzzy Finite State Machines, that ‘allow for nondiscrete states and transitions’ (Lecky-Thompson, 2008; 127). Especially suitable for situations in which multiple behaviours are logically required, FuFSM enable AI units to display multiple states at once and the possibility to transition to multiple new states simultaneously. Each state has a percentage portion that will impact on the next transition. These values increase or decrease according to the context. A guard in a patrolling state may be on alert state, and this may increase by several degrees before shifting to an attack state. A variety of values can be inserted in each state and will impact the transition. Lecky-Thompson indicates how ‘health, simulated stress, hunger, aggression’ (2008; 128) are values that can be added to the states of animal NPCs to provide a more realistic state transition process.

Champandard also suggests how emotions can be created as finite states and integrated in the FuFSM AI architecture. Another variation of FSM in guiding unit behaviour is represented by behaviour trees, formally known as directed acyclic graphs. Bearing a more structured, hierarchical form, behaviour trees present a network of behaviours where each type of behaviour is a node preceded and followed by sub-trees. Unlike the standard FSM, that respond to external stimuli from the environment and from the player's input, behaviour trees respond to higher-level AI planning techniques in which courses of action and therefore sets of behaviours are selected according to whether or not they successfully serve the function of reaching a specified objective. Behaviours appear as self-contained or modular states, present no transitions and can therefore be reused in a smooth manner to serve the planned goal. An algorithm searches among the possible courses of action, from the tree roots through all branches and leaves. Each behaviour node undergoes a validation that returns negative or positive feedback. Nodes can be searched in order until one validates (priority search), are by using a stochastic method, they are all evaluated and a random valid node is selected to add variety of action. What results from using behaviour trees is a more autonomous behaviour from NPC units that depends less on player's input.

Finally, AI is also implemented at the environmental level, and this can be especially observed in simulators that offer player the possibility to build and control large systems such as cities, societies, civilizations and even planetary systems and galaxies, and observe how they evolve. In this case, as Lecky-Thompson suggests, the AI 'doesn't deal with opponents, but with the game universe itself' and 'handles the game universe's reaction to the player's actions' (2008; 31). In simulations such as *SimCity*, for example, players need to manage an entire city (or cities) from terraforming and building the basic foundations to the constructions of houses, buildings, business districts, countryside farms, road networks, transportation systems, resource gathering and so on. A combination of the AI techniques explored above is used to provide interaction and responses from the environment to the player's input. Path-finding is used to direct the traffic or the pedestrians from place to place, using A* search and heuristics to determine the shortest path. Planning high and low level AI also guides the inhabitants who may have various individual goals to achieve that emulate real life, such as job finding, shopping etc. Places of interest will attract more traffic and pedestrians, and the way the player handles the resources or maintains services and utilities will impact the wealth of the city and the population growth.

Another example of environmental AI can be observed in *The Sims* series that attempts to simulate the life of a human family and places emphasis on behaviour and emotional states. After specifying values as to the personality and characteristics of their Sims, players can either simply observe how these behave and live, or intervene and direct their actions. Each Sims will have a set of physical, mental and social desires to satisfy, and these can cover social interactions, family building and finding jobs, buying a larger house or simply spending time sleeping, watching TV or relaxing by a swimming pool in the garden. Aside from path-finding methods, it is easy to understand that behaviour trees are heavily implemented in this case, in order to make Sims more autonomous and therefore more entertaining to watch. Sims will take action according to which need has to be satisfied and this will also depend upon their personality. The personality comes from the combination of traits and wishes, and can therefore have a large number of variations. The AI governs the Sims' decisions based on long-term wishes and random short-term objectives that are included in the satisfaction of mental or physical needs. The game world also provides constant information to the NPCs through the objects around them. Each object feeds information on how it will affect the Sims' mood and how it is to be used. This allows Sims to interact with their environment in interesting and varied ways without the player's intervention. For example, a Sim needs to satisfy his or her "fun" need, and can choose between a pinball machine and a book. Since the personality will determined which object is used, a serious Sim will likely read the book while a playful one will opt for the pinball machine.

The Sims, due to its ambition of re-creating, along general lines, the life of a human being with some emotional, social and mental depth, is unique in its kind and is a good example of combined environmental AI that places a high emphasis on NPCs autonomous behaviour. However, regardless of the diversity of events that can be observed, deterministic methods are employed and this means a total finite number of actions that, although may repeat with less frequency, can be predicted by simply analysing the values that make up a given Sim and those of the objects in its surrounding environment. By using deterministic AI methods, Sims or NPCs in general do not learn, evolve and adapt to their environment, and their actions, varied though they may be, are determined by pre-established designs and are sometimes simply made random or probabilistic in order to reduce repetition. Their behaviour is not emergent in the sense that it does not pass certain domain-restricted boundaries. Finite State Machines, Fuzzy Finite State Machines and Behaviour Trees have a finite pool of possible actions and combinations NPC units will adopt, though the order with which this will happen can vary. For example, in latest titles such as *Metro: Last Light* (4A Games, 2013), or the latest *Tomb Raider* (Crystal Dynamics, 2013), enemy units assume multiple states at once. If a unit is found alone patrolling a location and detects the player's presence, it may attack, call for backup, hide or flee, or any combination in between, but we would not expect the unit to suddenly drop the weapon and beg for his/her life, or offer to fight along with the player or pretend dead if these states have not been included beforehand by designers. As we have observed throughout the several examples of standard game AI techniques, what appears clear is that in order to provide the illusion of intelligence, variety plays an important role, along with a degree of randomness and shortcuts allowing NPC units to imitate human behaviour.

4.1.2 *Finite State Machines and game narrative structures*

FSM models, seen as general scripting systems governing the behaviour of interactive game elements, can be utilized to control and diversify the narrative structures of video games. This can occur by directly modelling the in-game dialogues, plot architecture and story branches, and/or indirectly by modelling the ecosystem of the game world so that events not related to the main storyline may "spontaneously" occur.

A suitable recent example of a large yet finite system of in-game dialogue interactions modelled through FSM logic can be seen in the *Mass Effect* trilogy (BioWare, 2007-2012). *Mass Effect* can be categorized as a science fiction action game with RPG elements. Players control a customizable character, named Shepard, in a fictional universe in which mankind has discovered mass effect relay systems allowing for faster-than-light (FLT) space travel across the galaxy. This has put humans in contact with a large number of alien civilizations that include both biological beings as well as synthetic life forms, the Geth, who have reached a sentient status, evolving through a neural network type of collective intelligence and pose the threat of conquering the entire galaxy. In order to prevent synthetic life from spreading across the galaxy and inhibiting the birth of biological life on suitable planets, a semi-organic entity known as the Reapers, appears every 100.000 years to carry out a "harvest cycle" aimed at purging the galaxy from all advanced sentient and synthetic life in order to maintain balance and pave the way for the birth and development of new life species. Facing the Reapers' menace represents the ultimate objective, with humans and the player's main character playing a leading role in responding to the Reapers' attacks. While this is the main story background, during most part of the three games players will concentrate on gathering resources to upgrade weapons and defence systems, as well as helping other alien species by accomplishing a number of missions in order to build alliances and thus prepare a strong opposing force in the final encounter with the Reapers.

While each of the three games can be considered as a standalone chapter with its own beginning and conclusion, players are able to import their own character along with all the decisions taken starting from the first chapter. These decisions are taken both through selecting from a large number of dialogue options while interacting with NPCs, and through actions taken during missions (i.e. whether or not to help a human colony, spare an enemy's life etc…). Since each of the chapters can have several endings and story variations, certain characters (including the main one), for example, may or may not reappear in the following games according to whether or not they survived, or may appear as hostile rather than friendly. The dialogue interactions take the form of a sliding wheel (as shown in the picture below), where players choose among a number of possible sentences that generate different responses from the NPCs.

Figure 14. Example of in-game dialogue options in *Mass Effect 2*

Once a choice is made, it is not possible to revert to another option, and this can sometimes lead to a failure in achieving a specific purpose (i.e. convincing a character to join the fight against the Reapers, provide financial resources or initiate a relationship). This consequential system also includes the "PermaDeath" feature which will impede certain characters who have died in the previous chapters from appearing again, as in the Suicide Mission of *Mass Effect 2*. Both types of decisions, dialogue and action ones, have an equally important impact for the rest of the story, and will tunnel the player into a particular story branch according to the combination of his/her decisions made during gameplay. "Side effects" of players' dialogue and action decisions regard the main character's personality orientation sliding across a scale that goes from Paragon (heroic) to Renegade (hostile). The availability of certain in-dialogue options such as intimidate/charm selections, or "interrupts", allowing the character to take a more physical approach during a conversation, will depend upon the current orientation status. *Mass Effect* represents a recent example of sophisticated narrative branching made possible by the insertion of large amounts of "decision nodes" guiding players through an intricate story tree with several ramifications. Each decision node is an input choice which will cause the rest of the story to transition into a specific state as output.

Spread across three titles, the narrative experience can thus be greatly diversified, increasing players' sense of personal agency in the game world. Riedl, Thue and Bulitko (2011) describe this system as POCL (Partial-Order Causal Link) narrative plan, in which 'nodes are operations…which, when executed, change the world state' (132). In the *Mass Effect* example, each node is represented by a possible decision which will affect the course of the story and will cause the narrated events to change or be re-arranged in a different order. The entire narrative structure is a Finite State Machine which presents an initial state, followed by a network of logically linked nodes/states representing narrative causality and the final outcome, which will be the result of the combination of nodes activated throughout the gameplay.

The diversity of narrative branches observed in *Mass Effect* is replaced by a diversity of world events featuring titles belonging to the sandbox genre, based on the concept of extensive nonlinear world exploration sessions detached from the main storyline. To motivate players to engage in free roaming across the vast maps, sandbox game worlds need to be interesting places with their own virtual ecosystem and with a number of events that can occur with or without the player’s direct interaction. In *Red Dead Redemption*, the game world is designed in such a way as to appear as an autonomous micro-world with a number of built-in randomized dynamical systems. An accelerated day/night cycle is accompanied by a randomized weather system, which is developed so as to have a direct impact upon the morphology of the terrain, on the vegetation and animals populating the areas as well as the inhabitants of the various settlements scattered across the region. An NPC will therefore take shelter under a tree in the haze of a sunny day, but will run towards the nearest settlement and inside a saloon during heavy rainfall. Likewise, if NPCs are travelling during the night, chances are that they will set up a small camp and light a fire for warmth and to keep wild animals at bay. During wet and humid conditions, the terrain will become slippery and muddy, making it difficult for the protagonist and his horse and all other NPCs to travel across steep ridges and uncertain slopes. Likewise, accidental fires may spread across less arid sections of the map in case of long periods of draught. Events involving NPCs may also randomly occur throughout the game world, with players being able to intervene if they are in the immediate vicinity. Indeed, the NPCs system is also supported by cause-effect architecture that is adds credibility to the virtual world. If the body of an enemy, for example, is left unattended outside a settlement, vultures, wolves, hyenas and other animals may be attracted by the carcass. Similarly, solitary carriages travelling through isolated regions may face robbery, or riots and shootouts may occur after a game a poker in a saloon or discussions may ensue if a girl is being harassed.

Aside from a number of unique events or encounters, which will happen only once, more random events, also known as “world events”, will happen regularly throughout the game session, could generate at any point across the map with the right combination of variables, and the player can decide to intervene and settle the disputes or simply observe as a bystander. The game world consists of an autonomous, time-driven state machine, with each state representing an input which will trigger NPCs’ state transitions. While the player has no control over the day/night and weather cycle, he or she will be able to interact with single NPC units and determine their next state. If NPC units are not interacted with, they will respond to the input provided by other NPCs and by the weather and day/night systems.

While *Mass Effect* and *Red Dead Redemption* offer a wide variety of situations and narrative possibilities, they remain finite systems. In *Mass Effect*, the narrative branches and story directions will eventually repeat once they have all been explored. Similarly, observing the world of *Red Dead Redemption* for extensive periods of time will finally reveal the same events and the same world dynamics. The order may change, but the events and characters' actions, will be identical and will not show complexity, emergent behaviour or unexpected surprises beyond their finite set of states through which they are scripted.

4.1.3 *Pseudo-Nondeterministic AI: Neural Networks, genetic algorithms and flocking*

Let us now shift the attention towards non-deterministic methods explored in game AI which approach the problem of intelligence from a different angle. At the basis of the methods that will be briefly discussed is the endeavour of setting the right conditions for NPC units not to display a fake, illusory intelligence, but to become independent entities that are capable of learning from their environment, adapt, evolve and thus display autonomous behaviour driven by factors such as survival. Artificial neural networks and genetic algorithms currently represent a promising approach for machine learning, have yielded significant results and though their appearance in games is still very limited, they appear to be one of the possible paths game AI may take in the future. Both models take inspiration from biological systems: Artificial neural networks are modelled after the neural structure of the animal brain, while genetic algorithms are designed to represent a synthetic model of Darwinian laws of evolution, the survival of the fittest. Both models try to recreate the process of adaptation, learning and survival that takes place in nature in a virtual environment. Furthermore, both approaches have the objective of making virtual units autonomous in their behaviour, and this is an important basis for the appearance of emergent behaviour. According to Gurney, artificial neural networks are defined as 'an interconnected assembly of simple processing elements, units or nodes, whose functionality is loosely based on the animal neuron' (1997; 1). Designed to provide a rudimentary model of the type of computation occurring in the brain, ANN consist of sets of neurons, that is, single processing units.

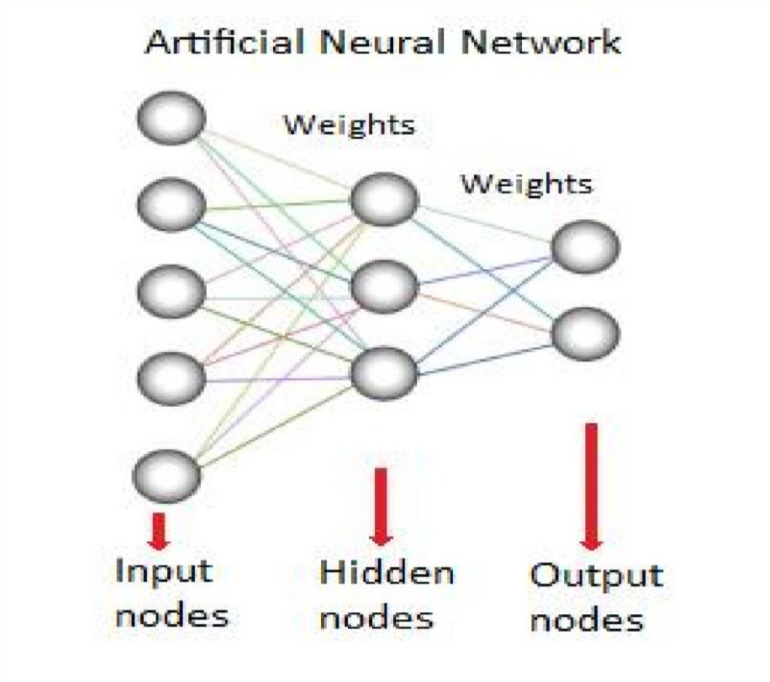


Figure 15. Model of a simple Artificial Neural Network

Each neuron, which in the figure appears as a node, has multiple connections to other neurons by means of weights, which replace the synapses of the biological brain. Artificial neurons can receive multiple inputs from the environment and from other neurons in the network, have an internal threshold value, or threshold logic unit (2), and produce single or parallel outputs. The figure above illustrates an ANN model which can receive a maximum of five external stimuli and can generate two parallel outputs.

The strength of the receiving input or signal is weighed in the interconnections. In order for a neuron to fire an output, the sum of the signal values needs to be greater than the threshold value of the neuron. The values of the weights can be adjusted, and the nodes forming the network can be trained to recognize several inputs and produce several outputs. The training occurs by means of a 'learning algorithm' (Hayden, 2012; 25), and consists in ensuring that the output produced by the network in a given situation is consistent with the type of input received. As Lecky-Thompson explains, 'if the output is slightly different from what's expected, we can say that the response of the neuron is almost correct, and we only need to change the importance of the input data slightly' (2008; 132). The importance of the input data can be changed by modifying the various signal values. In short, a neural network, which can be in the form of physical hardware units (such as exploratory rovers for example), or simulated in software, has the ability to learn and generalize. As Hayden points out, the objective is to enable the unit's 'production of reasonable outputs for inputs not encountered during training' (2012; 25). A first major benefit of neural networks in game design comes from the autonomous decision making ability of NPCs which overcomes the problem of building complex FSM structures. Bourg and Seeman explain how ANN 'relegates key decision making processes to one or more trained neural networks' (2004; 357). Of equal importance is the ability of adapting continuously as the game is played. However, these two factors also make the implementation of ANN in games problematic, as it represents an obstacle for testing and predicting.

Attempts have been made to implement Artificial Neural Networks, most notably in the Rally racing game *Colin McRae 2* (Codemasters, 2000). AI developer Jeff Hannan used a single layer of artificial neurons, known as Perceptron (Champandard, 2004; 195), to enable AI cars to extract visual patterns from images and used the input to stay on the racing line. In this case the ANN is used to control the movement of NPC. Its use, albeit limited, also extends to fighting games, where the network is trained to anticipate player's next move by using previous inputs to produce predictions.

While ANN are designed to encourage autonomous decision making abilities and facing uncertain situations independently by emulating the brain's input multi-processing structure, genetic algorithms take inspiration from the evolutionary process of survival of the fittest. When applied to a population of NPCs, genetic algorithms determine the rules by which the interaction of an initial generation with particular traits with the environment leads to a selection process based on ranking fitness (Bourg&Seeman, 2004; 411). According to the rules specified in the fitness parameters, only the most successful traits of the members of the first generation will be passed on to the second generation. In terms of problem-solving computation, 'genetic algorithms produce increasingly capable problem solutions [to a specific domain] by operating on populations of candidate problem solutions (Luger, 2009; 508). In game design, the initial population may have different traits that are evaluated according to their fitness for the environment. Much like the biological realm, the traits (or chromosomes) of the most successful entities are combined through "genetic operators" (Luger, 2009; 510) and give rise to the members of the second generation. The recombination process of successful individuals is paralleled by a random mutation command that changes randomly the genetic code of certain individuals. In a game environment, therefore, NPCs will retain behaviour that is successful for their environment and improve it, while invalid behaviours will be eliminated as generations succeed one another.

Artificial Neural Networks and Genetic Algorithms are perhaps the best examples of AI that can give rise to semi-autonomous behaviour. Limited though their application in game design is, they are nevertheless useful tools for ‘providing life-like variations from standard patterns as a way to counteract predictability’ (2009; 282). Much of their use is in what is known as Artificial Life, defined by Lecky-Thompson as ‘a way to express the AI in a more natural embodiment’ (2009; 60). Through ANN and GA methods, A-life can make mistakes that are not scripted, improve on these mistakes and overcome uncertain situations in a more autonomous manner. Also adding group dynamics such as flocking can have a positive effect in terms of generating emergent, unexpected behaviours.

Combining Artificial Neural Networks with a genetic framework allowing NPCs to retain successful traits of the previous generations leads to interesting results in machine learning. One of the most successful experiments integrating these two nondeterministic AI techniques comes from Stephen Grand’s works on the series known as *Creatures* (Grand, 1996 – 2001), whose development started in 1996 and gave birth to various releases until 2001. Initially conceived as an experiment of Artificial Life similar to the Japanese portable pet known as *Tamagotchi*, Creatures expanded the concept or raising a virtual pet by introducing a learning architecture that would enable the virtual creatures to display intelligent and emergent behaviours autonomously. While the virtual pets of *Tamagotchi*, developed by Yokoi and Maita in 1996, resembled what will be later observed in *The Sims*, namely a life simulation based on parameters of happiness, discipline and physical desires that would lead to a limited number of outcomes according to the player’s level of care towards the pet (Early death, long life, sickness or health etc…), the virtual “aliens” of *Creatures*, known as Norms, were raised in a virtual environment scattered with objects, predators, and other Norms to interact with. Each *Creature*, defined by Grand as autonomous software agent (Grand, 1996), first hatched in an egg, lived in a twodimensional world, was endowed with a neural network containing attention-directing, decision making and perception lobes. These, according to Grand, allowed for a ‘system capable of generalizing from previously learned relationships to novel situations’ (1996; 5). The learning occurred as a reinforcement process through which the player could punish or reward the creature during the interaction with the environment. Punishment and reward acts affect the strengths of inhibitory or excitatory signals in the weights (synapses) of the neural network. In short, players are training the neural network to fire correct outputs according to the different interactive contexts. Since the Norms can mate and re-produce, the genetic algorithm allows for retention of successful traits learned by the previous generation, along with the insertion of a random system for mutating genes. The genetic coding embraces not only the Norms' positive and negative feedback by interacting with the environment, but also extends to include a survival factor in the form of Grendels, predators that can kill or infect the Norms.

Started as a simple 'exercise in engineering' (7), *Creatures* is to date the strongest example of Artificial Life in a game environment. Interesting behaviour resulting from the Norms' ability to learn, especially regarding social interactions between them, has been observed in a few instances as going beyond the designers' expectations and predictions. Grand mentions cases of 'cooperation in playing with a ball, or chase scenes resulting from unrequited love' (7). One player (Frank, 2012) recalls her experience with one of the creatures she raised being extremely affected by the death of her companion and spending long period of game hours nearby the dead body. Regardless of all the learning devoted to the survival of the creature, Jenn's Norm refused to abandon the body of her dead companion until she died of starvation. While Grand points that 'it is very difficult to establish how much of this is genuine and how much is conferred by an observer's tendency to anthropomorphism' (1996; 7), an experiment such as *Creatures*, which is designed to give rise to a wide variety of independent behaviour is certainly a solid premise for creating the conditions that may give rise to interesting forms of emergent behaviour and therefore emergent (though simplistic) narrative. From a technical point of view, taking Lecky-Thompson's definition of emergent behaviour as and aspect of game design which is 'the end result [that] is more than just the expected sum of its parts' (2009; 150), *Creatures* is arguably a promising achievement. It is however, also rare, with only a limited number of successive titles heading towards the same direction. Most notably in the *Black&White* series, a RTS title in which players assume the role of a god and needs to obtain the benevolence of every NPC in the game, a creature was introduced displaying the ability to learn from the interaction with the user, the NPCs and the environment. Although the genetic algorithm was not employed, as the reproduction aspects were removed, the creature presented the same learning ability thanks to a reinforcement driven neural network and with the addition of a belief-desire system modelled after Bratman's model of human practical reasoning (1999) known as Belief-Desire-Intention (BDI) and a behaviour tree leading the creature to choose the best course of actions to satisfy its desires.

Aside from neural networks and genetic algorithms, a third AI technique, known as Flocking, has the potential for complex behaviour, especially when compared to the study and observation of dynamic systems reaching complexity from simple initial rules and conditions. Based on a 3D model created by Craig Reynolds in 1986 known as Boids, which represented the simulation of coordinated animal motion such as that of bird flocks and fish schools, flocking has become an AI technique used in game design to cater for the motion of secondary environmental element so as to remove the need for scripting the path of each individual entity of the group. According to Reynolds, 'the aggregate motion of the simulated flock is the result of the dense interaction of the relatively simple behaviours of the individual simulated birds' (1987; 25). The behaviour of the single units is made of three simple rules (Bourg&Seeman, 2004; 86). The first rule, cohesion, directs each unit towards the average position of its neighbours. This is followed by the rule of alignment, whereby the units align themselves to the average heading of their neighbours. Finally, a separation rule prevents the units from colliding into each other. With a fine-tuning and balancing of the steering forces applied to enforce the three rules, the end result is a fluid and seemingly natural motion and an emergent complexity of patterns and formations. Obstacle avoidance rules are added in game design, for example when emulating crowds in busy environments, in order to minimize collisions with objects present in the environment.

4.1.4 *Escaping Determinism*

The previous discussion of game AI techniques has helped us establish the dominance of deterministic structures in game design. Such awareness is important in that it is necessary to understand the type of environment in which nondeterministic Cellular Automata may be integrated. In game design, according to the type of system being observed, the behaviour of NPCs may appear to be probabilistic, random or intelligent. We have seen how a stochastic logic currently represents the only established method used in game AI to inject a controlled degree of diversity in the game world and among NPC units in their interaction with themselves, with the virtual environment and with the player. Yet, the probabilistic state changes deriving from stochastic techniques do not counteract the finite nature of the number of states a unit or the game world can assume which lead to an inevitable repetitiveness. Consequently, after a few playthrouhgs, a game will eventually fail in providing a sense of novelty and surprise.

On the other hand, nondeterministic methods such as flocking, Genetic Algorithms and Neural Networks represent alternative pioneering attempts to provide synthetic agents with autonomous, rather than probabilistic, behaviours. However, with the exception of flocking, used as a simple decorative element such as the Boids in *Half-Life* (Valve, 1998) the complexities and computing resources involved in developing ANN and GA based AI structures have relegated the implementation of these techniques in game design to experimental curiosities rather than fully integrated architectures.

Let us therefore consider this question: could an AI game system be designed so as to accommodate, for example, the “simple-rule-to-complexity” principles behind Cellular Automata and nonlinear dynamical systems in order to promote emergent behaviour and unpredictable outcomes? Can this emergent complexity be harnessed through innovative AI techniques and bring emergent narratives one step closer to reality? In the next part of this chapter we will explore several scenarios in which Cellular Automata can be successfully integrated in the game’s AI architecture and direct the behaviour of game world elements and virtual agents without disrupting the overall gaming experience. We will consider these principles as necessary to escape determinism in game design and use them formulate a nondeterministic model addressing the close-ended and predictable nature of narrative structures.

4.2 Adding Complexity to the Video Game Environment

In the previous chapter it has been possible to gain an understanding of the types of development and evolution of Cellular Automata. We have seen how certain types of Cellular Automata simulations set to run in a computer environment display properties which characterize them as nonlinear dynamical systems, and which makes them suitable as a model to address determinism in video game narrative structures. These properties are unpredictability of future outcomes, nonlinearity in the evolutionary trajectories, high sensitivity to the initial conditions and perturbations which tend to grow exponentially rather than proportionately. We have seen how research also discusses further properties which can arise under certain circumstances. One of these properties is irreversibility, which makes the configuration of certain types of Cellular Automata simulations impossible to revert back to their initial conditions. Wolfram has explained how during the evolutionary trajectory, observed as the Automata develop through several time-steps across the grid, information regarding the immediate previous step of a given configuration becomes increasingly blurred until it has a multiple number of possible predecessors instead of one.

Another characteristic is the ability of Cellular Automata to give rise to fractals and patterns bearing the property of self-similarity, which results from the Automata following periodic or semi-regular patterns guided by the principle of random distribution. All these elements not only make it possible to identify Cellular Automata as a nonlinear dynamical system, but also enable researchers to use them as a model to understand the mechanics of complex and chaotic systems found in nature, as see in the examples in Chapter 3. It has been shown how Cellular Automata can have not only a wide variety of forms and configurations but also display significantly different behaviours and properties according to which rules and conditions are initially selected. Nevertheless, only some types of rules will be irreversible and have self-similar patterns, while most will retain the features of unpredictability and sensitivity to initial rules and real-time (internal or external) perturbations.

In formulating a method for integrating Cellular Automata in video games we will look primarily at those factors which tend to be preserved: unpredictability, rule and perturbation sensitivity and nonlinearity. These features will lead some Cellular Automata populations to display complexity of patterns and behaviour. Some populations will continue to grow and expand on the grid by self-reproduction, while others may travel across the grid remaining in stable or quasi-periodic formations. In other simulations we may observe Cellular Automata disappear after a number of time-steps or reach a state of equilibrium on a certain location on the grid and last indefinitely. These very factors--the possibility of a multitude of outcomes, and the very uncertainty in predicting which one of these will occur, when, in which form and in which spatial coordinates—will be harnessed to inject nondeterminism in game design.

Earlier in this chapter it has been shown how the artificial intelligence used in video games tends to rely primarily on deterministic architectures and, more specifically, on Finite State Machine systems governing individual agents as well as unit groups through higher and lower level behavioural trees. We have seen also how designers, in order to promote more variety and minimize repetitiveness, may add probabilistic elements- therefore making the state change of a given unit less predictable, or may enable agents to display semi-autonomous and learning behaviour which adapts to the player's characteristics and/or the game environment by implementing Artificial Neural Networks and Genetic Algorithms. However, despite the variety added by these non-deterministic scenarios, the finite nature of the synthetic agents' possible states remains unchanged, as does their generally controlled behavioural display, which can be predicted with a fair degree of certainty. In a stochastic scenario, an enemy unit possessing four specific states (i.e. resting, patrolling, suspicious, alert) may randomly activate any one of them as it responds to the player's input, but will still operate within the pre-established set of behaviours determined by the designer. Similarly, AI opponents using Neural Networks to adapt and respond effectively to the player's strategy will be still bound to a finite set of behaviours and draw from a pre-determined set of moves and actions. Opponents in car racing games featuring sophisticated AI neural nets, for example, will re-adjust their strategy according to the player's level of aggressiveness or cautiousness, re-modelling their decisions in real-time by drawing from a pool of pre-set approaches. After registering the player's driving characteristics during one race, the AI will deploy a set of responses in successive races, attempting to further refine a counter strategy to best adapt to how the player is driving. Although this process can be thought of occurring in a semi-autonomous manner, the overall objective for the AI is to make the computer opponents' choices appear credible rather than intelligent or unpredictable. This is executed by allowing the AI to choose from a finite set of credible strategies. In short, the interesting non-deterministic alternatives offered in current game AI technology, while providing more credibility compared to strictly linear techniques, are limited by random cycles of set behaviours. Behaviours themselves do not undergo any variations, and complex emergent behaviour cannot occur.

The approach of Cellular Automata, instead, has the potential to bring an innovative nondeterministic element which does not confine unit populations in a pre-established set of behaviours. On the contrary, it renders the very nature of future behaviours unknown before they take form on the screen during the simulation, making them essentially unpredictable.

Before understanding through several examples what type of changes this type of experimentation of Cellular Automata simulations in a video game environment may bring, and how it would address its deterministic nature, it is important to understand why these elements are crucial. We have seen how, through Wolfram's extensive observations and experiments, a Cellular Automata simulation must be run in order to see what the ending outcome will be. There is no algorithm which can bypass the evolutionary journey of a Cellular Automata population and calculate the final outcomes prior to the completion of the simulation. It is this type of unpredictability, which goes beyond the control of the designer and can go beyond the expectations of the observer, that this study intends to inject in a video game environment and which is considered a nondeterministic response to address the deterministic nature of video game narrative structures.

It is important, therefore, not to misunderstand non-determinism linked to unpredictability with non-finiteness. Video games are finite in nature in that they are composed of a limited number of elements. Furthermore, they are also coded as to produce a finite number of visual and audio outputs. This notion of finite-ness goes beyond the software boundaries, when we consider how the physical reality, nature itself, our complex brain and the observable universe are made of a finite number of constituents and atoms. It is instead the complexity which cannot be predicted by looking at the single properties and states of the individual constituents of a system to represent an answer to determinism. As a species we have dissected and observed the single parts that form our brain, from the cerebral cortex to the neurons and synapses and how they negotiate electrical impulses, and finally to the microtubules inside the neurons. Yet we have not been able to understand the emergence of the phenomenon of consciousness or even, in Conway's words, what makes 'one cat behave differently to another'.

4.3 Fundamental Design Principles: Level of Integration into Processing Architecture

In choosing which type of Cellular Automata simulation would be more suitable in a game environment, there are several important factors that need to be considered. Firstly, the Cellular Automata model needs to be integrated within the existing framework in which games normally operate in a discreet manner. More specifically, the Cellular Automata themselves, with the familiar configuration of grids and counters will not constitute a direct graphics component during gameplay and will therefore not be visualized. One principal reason derives from the intention of employing the Cellular Automata system as a background, discrete architecture to be integrated as an additional layer to the existing game AI. Of all the elements constituting the game world and visualized on the screen, some of these will be directly controlled, in terms of behaviour and development, by the discreet Cellular Automata component. Therefore, while the Cellular Automata simulation remains a hidden process, the data that it generates is fed into the game system in real-time and translated accordingly into game-related outputs.

4.3.1 *Computational Role*

The second factor to bear in mind regards which processing unit will be employed to run the necessary calculations for the Cellular Automata simulation. Modern games are normally designed to take advantage of both Central Processing Units (CPUs) and Graphics Processing Units (GPUs). These will handle all the tasks needed to correctly display and run the game on the user's device through a hierarchy which varies according to the type of game, the numbers of element generated and displayed at any one time and the numbers of variables which need to be calculated in the background. GPUs generally run calculations in order to render all textures of the 3D models, visual effects and in some cases physics reactions of the game world. CPUs, on the other hand, are employed to run the AI architecture, game variables and additional processing data in the presence of large maps and large amounts of simultaneous in-game units. Real-time or turn-based strategy games as well as god games, for example, place less emphasis on graphics rendering and rely more heavily on the CPU for background calculations to process variables relating to the several aspects of development of game entities such as economy, population satisfaction or autonomous traffic and pedestrian systems as well as unit-to-unit fight variables during battles involving armies. On the other hand, action-oriented games providing a cinematic experience place more workload on the GPU in order to render high numbers of polygons and texture resolutions and realistic lighting and world effects. Since our model of Cellular Automata will run in the background as an additional AI layer, its calculations will be handled by the CPU. The type of games which will be discussed in our examples of Cellular Automata integration will be primarily open-world games with extensive maps or strategy and simulation games with large amounts of variables. In the light of the heavy CPU usage, we will need to contain the complexity and extension of the configuration of our CA model.

4.3.2 *Selectivity*

This leads directly to the third principle, derived from a realistic perception of the current game industry. It involves the need maintain a certain level of simplicity and containment in the Cellular Automata population, and relegate them only to confined areas of the map or in partial controlled of specific variables. The purpose of this model is to create pockets of complexity and unpredictability in the game environment rather than embracing the totality of the gaming experience. This would translate in unpredictable events which are localized and would therefore not disrupt the gameplay experience based on the deterministic but at the same time successful formula game designers and publishers may not be willing to abandon. In more experimental settings it may be possible to envision a game built primarily with the purpose of harnessing Cellular Automata technology and let all game entities develop according to it. In this case, one immediate consequence would be that elements such as the role and agency of the player and the very concept of gameplay may diverge significantly from current titles, leading to an experience which may be more observational. While users would still be able to determine the initial rules and intervene during the simulation by causing perturbations to the system, the active and linear gameplay element, which is fundamental in today’s gaming industry, would not represent, at least at the beginning, the core of the experience. Later in this chapter we will explore a game prototype for how future work on game design may adopt Cellular Automata as the predominant framework in which most game entities respond to a nonlinear dynamical behaviour. A prototype game will be devised along with a discussion of how events and narratives may be affected, serving as a starting reference for designers which may be interested in implementing this type of nondeterministic technology. However, since the principal objective of the study is to address the deterministic nature of present day games and their narrative structures, examples will be first discussed where Cellular Automata integrate into current game titles and genres. Choosing to consider different genres rather than focusing on one single game derives from the intention to explore a variety of ways in which Cellular Automata can be applied. Furthermore, considering the resources Cellular Automata would need in terms of spatial and time coordinates in order to evolve, it will be shown how certain genres appear to be more suitable than other for implementing this model. Looking at current games also offers the possibility of understanding which scenarios lend themselves better to the emergence of nonlinear and complex entities emerging from Cellular Automata simulations and where these may have a more effective impact on the narrative and nature of events occurring in the game as well as be less invasive or disruptive in terms of flowing gameplay experience.

One suitable Cellular Automata simulation meeting the three requirements discussed above, namely discreetness, appropriate CPU load and containment/simplicity of configuration of Cellular Automata populations, is represented by the same configuration employed in Conway's *Game of Life*. This configuration would consist of a twodimensional square grid to be populated by automata possessing the two possible states of on/off or dead/alive. This type of configuration with one-dimensional automata is also known as elementary Cellular Automata. As with Conway's model, the population of automata would develop through a discrete temporal system in which every time step represents the next generation and the next evolutionary state. More specifically, as observed in the various figures presented in chapter 3, the evolution of the automata population occurs across a unified time-space trajectory, where each step corresponds simultaneously to the passing of a time-unit and a directional step of the automata across the grid. This model employs the Moore-neighbourhood, which consists of each square being touched by eight possible neighbours. Rules set at the beginning of the simulation will determine each automaton's state transition by dictating how it interacts with the eight surrounding squares. These interactions will lead to each automaton to be dead or alive in the next generation. In addition to these fundamental components, initial rules should therefore be chosen which will be applied recursively at each generational step. We have seen how Conway's rule 2/3/3 of overpopulation/isolation/survival was capable of generating a wide variety of complex patterns guided by unexpected behaviours. Formations showing complexity such as still lifes, oscillators and translating oscillators would emerge according to arbitrary selections of the number and starting positions of initial clusters of automata. The configuration so far described, inclusive of a flexible system enabling the selection of initial rules and settings could be integrated in the CA model proposed in this study.

4.4 In-Game Integration

As discussed earlier, integration of the selected Cellular Automaton model into game architecture is via a discrete background process handled by the CPU. In-game elements and units are selected whose development or behaviour will be dependent on the evolution of the CA model. These game entities receive real-time feedback from the Cellular Automata simulation and change accordingly. This feedback is communicated to the GPU which graphically translates the data on the map in real-time. In short, the graphics engine receives instructions to read the results and apply them in real time to the in-game entities and on a visual level. A multi-core CPU environment, which has become the norm in present day home computing, would also offer the possibility of running multiple separate Cellular Automata simulations simultaneously.

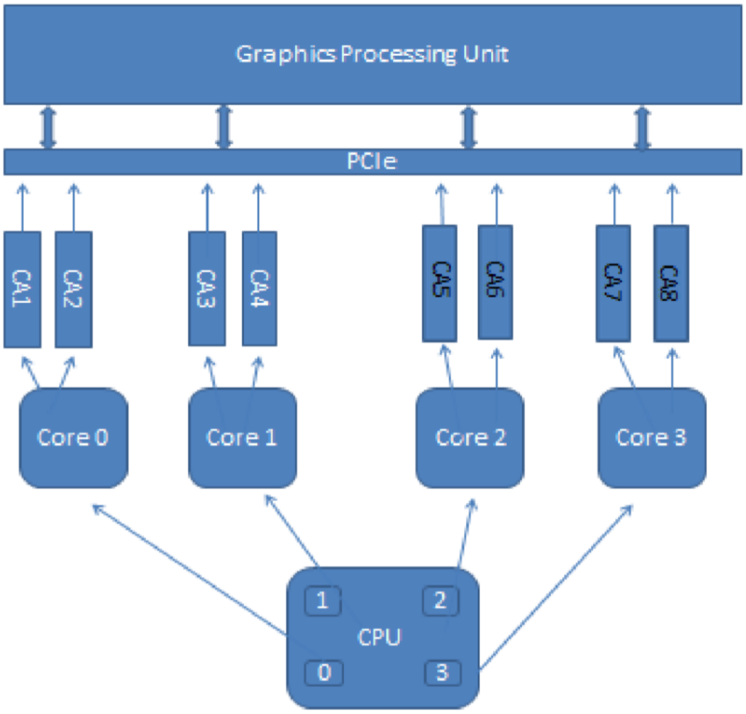


Figure 16. Distribution of multiple Cellular Automata in a quad-core CPU environment

The figure shows a standard quad-core CPU configuration and the how the single cores feed the Cellular Automata simulations to the GPU. Aside from the parallelism generated by multiple cores, the number of independent Cellular Automata simulations which can be run simultaneously can be doubled thanks to the multi-threading capabilities of each core.

A specific area on the game world represents a 3D counterpart of the two dimensional grid and serves as the stage for the in-game entities controlled by the Cellular Automata to evolve. In this scenario, also the frequency or refresh rate must be established with which the game engine reads the Cellular Automata simulation and applies the results. This could be executed in real time or at certain intervals, for example after a given number of game hours. It would also be reasonable to control the pace of the temporal trajectory of the Cellular Automata simulation, in order to facilitate the feedback loop and the real time rendering of the changes during the evolution.

We have said that a flexible system should be introduced to maintain variety of initial rules and starting conditions. Several steps can be taken in this regard to minimize repetition and promote unpredictability, all of them dependent on the degree of control given to the player.

For example, designers can decide to implement an automatic system, beyond the player's control, which can randomize the initial rules and conditions every time a new single player campaign is started. Alternatively this randomization system can be made available to players as an option in the game's menu, with the possibility of changing the starting parameters. The position and number of initial clusters of automata constitute one changeable setting, and the initial rules can be expanded beyond Conway's rule 2/3/3 by borrowing from the 256 possible rules for elementary Cellular Automata derived by Wolfram. Players, or the system itself, could select these rules arbitrarily. Combining the 256 rules with the coordinates of the grid representing potential starting positions it becomes possible to greatly increase the longevity of the game, as it would generate a large number of different scenarios at every new narrative sequence. Directly related in this regard is the choice whether to implement a finite or continuous grid. While an unbounded grid would benefit the variety of in-game scenarios by connecting the expansion of the territory with the expansion of the game units driven by Cellular Automata simulations, this would require the use of procedural content generation. Kushner and Sedovich (2014) explain how using this method can automatize the generation of textures by instructing the graphics engine to create 'algorithmically rather than manually' the 'colour of each pixel' forming the textures. In their tutorial, they explain how many landscape features can be extended such as ocean floors, rocks and canyons, water surfaces and so on. While this technique is becoming more available in current generation graphics engine, it is important to consider how the majority of games still rely on more traditional finite world and would therefore be more probable candidates for the implementation of Cellular Automata. Conversely, a game built to maximize the role of Cellular Automata, as the one which will be discussed later, would have procedural content generation among its requirements in order to provide unbounded space for the evolution and expansion of Cellular Automata populations.

4.4.1 *Integrating Cellular Automata in Current Game Scenarios*

The issues discussed above help shed light on an undeniable and recurring problem in game design. This is represented namely by the contrast between the need to maintain game development within the boundaries of the formula that has made the medium successful over the decades since its inception, and at the same time the need to bring novelty and innovation to aspects other than the look and size of the game world and number of character's animations, such as game AI. Since one of the crucial aspects of the medium in the form of the challenge it offers to players is governed by AI, re-adjusting it by making it increasingly sophisticated and by introducing alternative methods such as neural networks, genetic algorithms and, in the case of this study, Cellular Automata, needs to be executed more carefully. Below examples will first be presented which reflect this careful approach. More particularly, the role Cellular Automata can play in scenarios taken from existing games will be explored by maintaining a realistic gameplay flow as an important priority. This indicates that the role of Cellular Automata may at first be secondary and relegated to safely defined boundaries, so as not to have a significant impact upon the rest of the game. The need for containing Cellular Automata will be addressed in more detail prior to the presentation of the examples. These examples, taken from different types of games, will also help us gain an initial understanding of which genres may lend themselves better to the implementation of Cellular Automata and which may be less compatible and have little room for nondeterministic outcomes. Following the first set of examples is a section dedicated to the discussion of a prototype game in which Cellular Automata are the dominating AI technology governing most entities in the game and therefore exercising a major impact upon the entire gameplay experience. Presenting these two types of examples has the objective of describing the potential of the Cellular Automata model for both the more immediate reality of game design and a possible direction this might take in the future. However, for both current and future game design, it is important to remember that, given the intricacies and many combinations of Cellular Automata rules, and the unpredictability of outcomes, it will be only after extensive testing that safe playable boundaries can be established for games employing this type of technique.

4.4.2 *Creating a Containment Zone for CA-driven Game Entities*

As specified above, the presence of populations of game units developing according to the Cellular Automata simulation would require specific sections of the map. These areas would constitute self-contained micro-worlds players could return to visit at different times during the campaign and would be relatively isolated from the playable portion of the world map. One primary reason for creating what may be considered a "containment zone" for populations or entities driven by Cellular Automata derives from the fact that, as stated earlier, it would introduce factors such as complexity and unpredictability in a controlled manner, while at the same time not conflicting with the flow and continuity of game progression and gameplay. Indeed, a zoo-like scenario, in which Cellular Automata populations develop within a confined space on the map of the game world represents a more realistic approach to the current state of game design. It has been discussed earlier how a priority in game development has long been that of ensuring that players are offered an entertaining gameplay experience based on a balanced mix of challenge, cinematic action and storyline. A conventional way to achieve this derives from extensive testing and a highly controlled AI architecture in which synthetic agents' reactions to players' input can be predicted and fine-tuned accordingly in order to appear logical and credible. Too difficult an AI, such as that which may emerge from survival strategies observed in Cellular Automata simulation, while representing a promising turn of events from an experimental perspective, may pose insurmountable challenges to players and potentially halt the game progression. Similarly, Cellular Automata unpredictability may lead to other types of unit behaviour that may prove inconsistent or illogical with the setting of a game developed within conventional design frameworks. Even in open-world settings, where non-linearity and free roaming are predominant, logical and/or credible AI responses appear to be crucial in motivating players to explore the game world. In the light of these factors, it can be assumed that a realistic introduction of Cellular Automata in current game design would need to be executed with the notion of non-invasiveness in mind. This careful approach to integrating new techniques within the existing AI architecture and initially relegating them to a secondary role can be observed, for example, with other non-deterministic AI methods discussed earlier in this chapter. By looking at the history of game development, it can be observed how initial uses of Artificial Neural Networks, genetic algorithms, Reynold's Boids as well as probabilistic methods such as fuzzy state machines (FuSM) in game design were subject to a cautious integration with AI frameworks primarily based on finite state machines and script algorithms. In some cases, the game entities controlled by these less predictable AI techniques predictable techniques were also subject, especially at the beginning, to confined and enclosed areas of the map, bearing a secondary, sometimes merely decorative role. For example, in the god game series of *Black&White*, designer P. Molineux introduced a game entity, known as the "creature", whose behaviour was governed by a neural network, and which players could train through a punishment-reward system. While the core gameplay element revolved around the more traditional god game formula, with players influencing the development of a population of natives on an island, the addition of the creature aimed at introducing an extra element of unpredictability. The creature was confined into a small area of the map, and would engage in a variety of behaviours which depended on how the player's type of training imparted. If sleeping and being quiet would earn the creature food or affectionate gesture, it would learn to display this behaviour when hungry or in need of affection. However, the creature would also indulge in negative behaviours and, for example, snatch some villagers and eat them. Bound by chains, players still had the possibility of freeing the creature and let it freely roam the island, and this would lead to interesting scenarios such as villagers worshipping the creature and obtaining protection against enemy tribes, as well as disruption caused by the creature killing everybody and destroying buildings and houses, forcing players to restart the campaign. Similarly, Reynolds' complex flight formations displayed by the Boids were integrated discreetly in Valve's first person shooter *Half Life* (Valve, 1998). Valve developers applied Reynolds' rules of separation, alignment and cohesion to govern the flight of inoffensive bird-like creatures (called Boids) hovering around an island towards the end of the story. Travelling as a flock, the Boids have one single animation "idle" and their synchronized flying patterns emerge autonomously through the implementation of the three simple rules. They carry no additional AI behaviour algorithms and are therefore unable to interact with the player. Again, also in this example, the emerging patterns shown by the Boids have a decorative function, are confined outside the reach of the player and have no impact on the gameplay or the story.

The above mentioned examples demonstrate how novel AI techniques are integrated discreetly so as not to disrupt the flow of the gameplay. The creature and the Boids are integrated within the game world in a zoo-like confined status and are still observable by the player. The same principle would therefore apply to a realistic integration of Cellular Automata in game design. It has been discussed how the nonlinear dynamical nature means that different initial conditions and minor perturbations during the simulation can alter significantly their development and behaviour. Unlike Reynolds' Boids and more similarly to the creature in Black&White, Cellular Automata simulation accept external input, and this may lead to interesting scenarios in which the corresponding game units may display emergent behaviour and complexity upon interaction with the player. However, other instances may also lead to phenomena such as unbounded growth and/or early disappearance of the Cellular Automata population.

4.4.3 *Applicability and Interactivity of Cellular Automata Configurations in Game Design*

Therefore, experimenting with several sets of initial conditions becomes paramount, especially since the objective of this study is to address the determinism of game narrative structures. It is important to allow game units governed by Cellular Automata to be able to interact with and accept input by the surrounding environment, with the NPCs present in the game world and with the player. Furthermore, deploying different initial configurations must also be followed by applying an external input at any given time after the simulation has started, to see which set can accept user interaction without generating incompatible outcomes like uncontrolled growth and/or disappearance. A useful starting point to experiment with Cellular Automata initial configurations by applying the rule of the Game of life is represented by the *Life Lexicon*, compiled by Stephen Silver. The *Life Lexicon* contains an extensive database of a wide variety of initial configurations and free software is provided for the user to run the simulations, modifying the starting sets and also intervening during the evolution of Cellular Automata populations. The software, which runs a simulation of two-dimensional elementary Cellular Automata on a infinite grid, represents an ideal scenario and reference for testing the several configurations and the effects of real-time interactions prior to applying them in a game environment. Furthermore, elements such as speed of evolution and view magnifications are provided in order to quickly visualize the results of a configuration at different scales. This facilitates the task of identifying initial conditions which may be suitable. For example, an oscillator with a period of four, known as *Clock II* for its shape, while permanently maintaining its rotating cycle, does not lend itself to external perturbations, and the Cellular Automata populations die or become still lifes if external input is applied. Conversely, one applicable configuration which responds positively to external input is represented by Flammenkamp’s *101*.

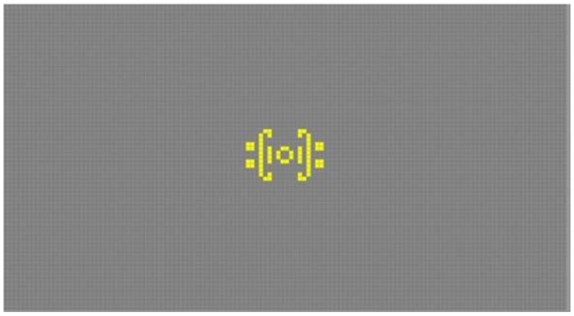


Figure 17. Oscillator-period I

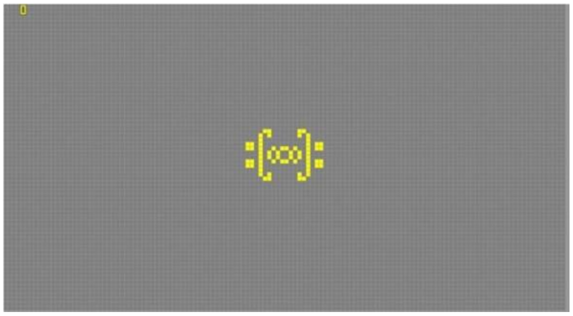


Figure 18. Oscillator-period II

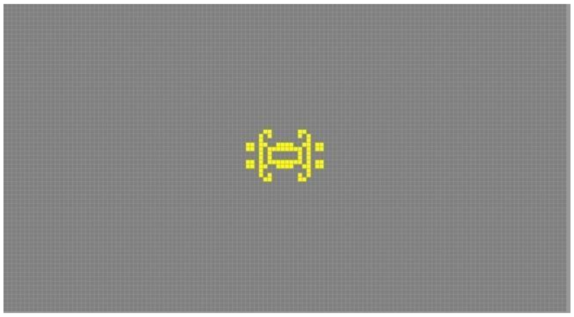


Figure 19. Oscillator-period III

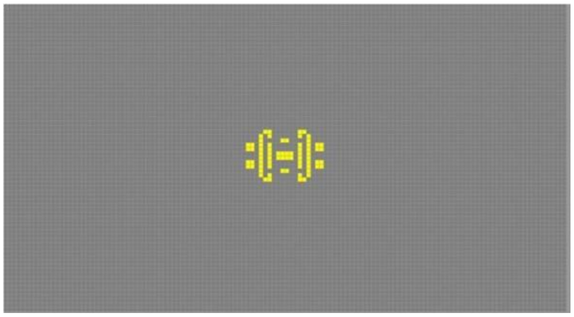


Figure 20. Oscillator-period IV

As can be observed from figures 17 to 20, the initial position of live Cellular Automata generates a permanent stable formation known as Oscillator. In this case, and in the absence of perturbations or external inputs, the Oscillator continues to exist indefinitely, with a stable external structure inside which an undergoing a four-phase periodic cycle can be detected. This type of formation is also known as Pulsar. With its internal structure displaying a regular shift of four positions, continuing for an infinite number of generations, the overall visual effect is that of a pulsating entity. This configuration could already provide an interesting behaviour for in-game entities. However, when the system is disturbed by means of external input, such as by adding one additional automaton, the configuration is subject to a drastic change, and different formations can be observed displaying unpredictable behaviours.

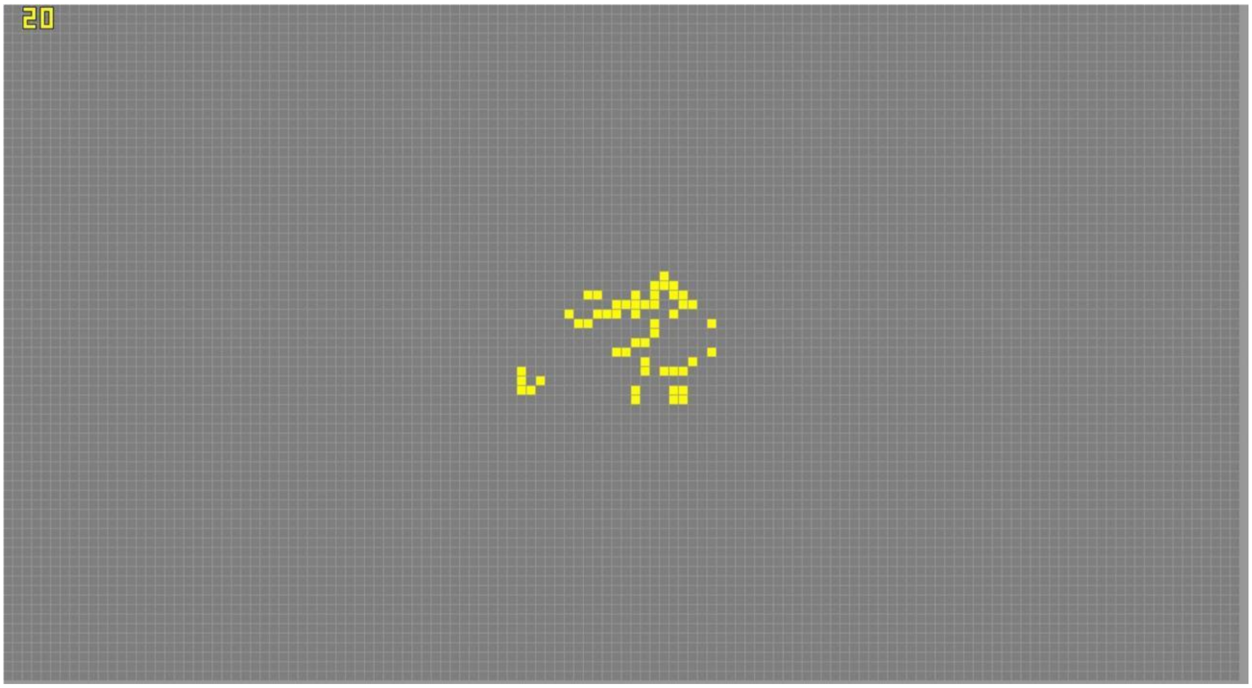


Figure 21. Perturbation after adding one live automaton

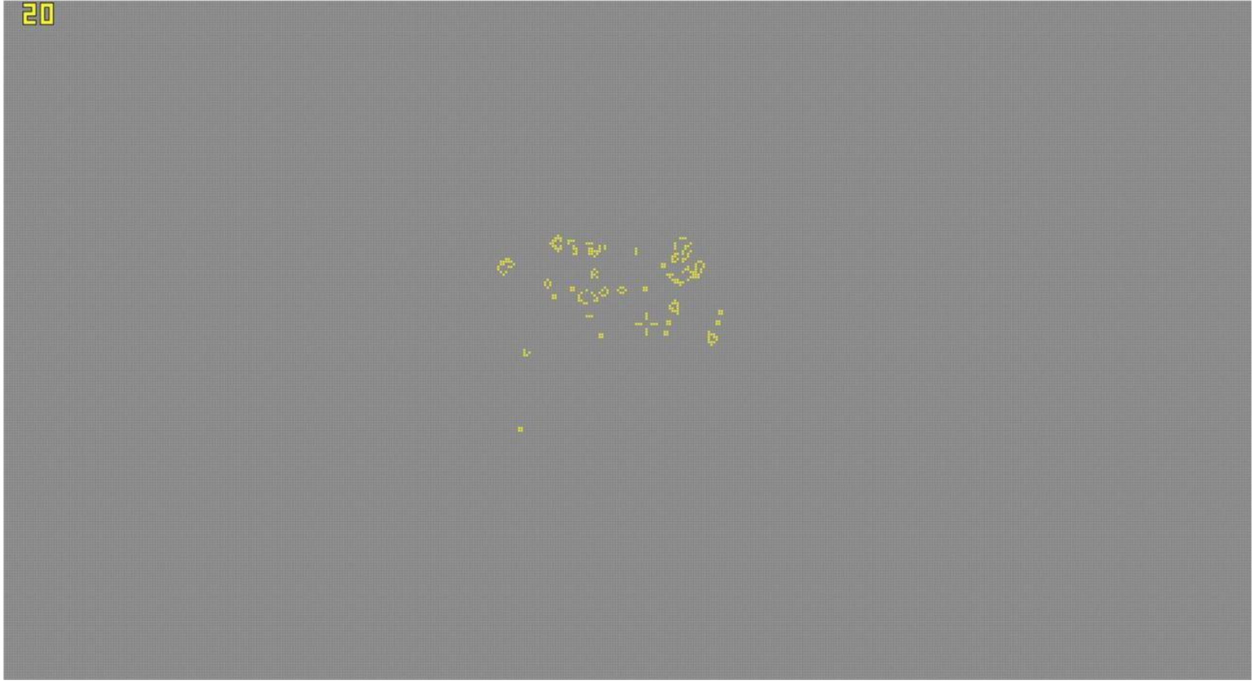


Figure 22. Activity caused by perturbation

In figures 21 and 22 it is possible to observe the drastic changes caused by the addition of a single automaton. Gliders and moving clusters of automata appear, as do static formations with periodic or unchanging cycles. As the travelling clusters come in contact with the static structures, these are in turn set into motion, changing into moving periodic or semiperiodic patterns and/or transforming into reproductive structures such as puffers and glider guns. In the testing of Flammenkampf's *101* set, subjecting the initial structure to perturbations leads to an interesting display of behaviours of the above mentioned phenomena which continues for approximately fifteen-hundred generations. Nevertheless, at the end of this time period, the Cellular Automata population neither disappears entirely from the grid, nor undergoes an explosive growth, and a single glider remains travelling southwards across the grid for an indefinite period of time. While testing a formation like *101*, but also true of a large number of oscillators such as Achim's *P144* (1994), Buckingham's *Airforce* (1972), or Trawick's *Candelabra*, is also interesting to see how applying an external input to still life clusters which have settled into a dormant state can work as a stimulus to suddenly reactivate them and set them again into motion. These oscillators are examples of Cellular Automata configurations that can be applied to a game environment as they are long lasting structures that can also be interacted with. However, aside from testing the initial configurations to find those which are more compatible with the game AI, it is also important to test the types of interactions and their effects, in order to map the inputs which have positive outcomes and remove from the code those which may have an excessively disruptive effect. Referring to a database such as *Life Lexicon* is an ideal starting point to understand which types of starting formations can be used within a game environment. Further experimentation can then take place by directly setting the initial conditions and running the simulation to test the results with and without perturbations.

The examples discussed represent applicable configurations for the model of Cellular Automata to be integrated in game design. They represent suitable candidates in terms of their non-disruptive response to external input. Using them in the model proposed not only would enable CA to have a more direct impact upon the nature of the events forming the narrative flow of a given title, but also may give rise to unpredictable and interesting types of behaviour never observed before in video games.

4.5 Game Scenarios: Suitable Genres for Cellular Automata Application

In looking for specific genres which may represent suitable candidates for the implementation of Cellular Automata, it is important to consider a number of factors. It has been discussed how a possible way to apply the Cellular Automata model would involve portions of the game map in large open worlds. Furthermore, additional applications may directly affect the control and development of visible and non-visible phenomena such as a civilization's economic growth, the behaviour of large groups of units such as friendly or enemy armies, as well as traffic flow and population growth in titles belonging to the simulation and RTS genres, where large amounts of hidden variables beyond the player's direct control play an important role in the overall outcome of the campaign.

Conversely, titles aiming at providing a more linear and cinematic experience as that seen in many FPS, may prove less suitable for an initial application of the model. Designed to deliver set pieces focusing on immediate action relying on scripted scenes, titles taking this direction tend to provide little or no freedom at all to players to explore the map (which often does not extend beyond the immediate field of action) and progress occurs by means of a narrow path with specific actions to be performed in a fixed order. Indeed, if we consider the nature of Cellular Automata as being a nonlinear dynamical system with unpredictable outcomes and possessing properties such as irreversibility and high sensitivity to initial conditions and perturbations, it then becomes clear that game genres opting for a controlled and scripted experience may not be compatible with the implementation of unpredictable AI. However, this does not necessarily limit Cellular Automata exclusively to the open world and simulation/rts genres. Indeed, two factors seem to be crucial for making Cellular Automata applicable and therefore widening their scope. These are represented by a large enough portion of the world map and/or the presence of a flexible form of multi-layered enemy AI. In game scenarios in which players have control of one or more characters and the action takes place directly on the game map, dedicated portions of the playable area are necessary in order to have a visual representation of the entities governed by the Cellular Automata model. The unpredictable and complex behaviour of Cellular Automata can furthermore be applied to in-game entities which pose a challenge to players, and be made to operate at higher levels, for example, by affecting the strategic decisions or the overall development (economy, growth, culture) of enemy AI.

Furthermore, a third field of application which, as it will be described in the examples below, may rely on a real-time translation of the complex visual patterns displayed by twodimensional Cellular Automata directly on the screen, is represented by 2-D side scrolling titles presenting mazes and structures to be navigated and/or moving enemies to overcome. Also in this case, part of the moving map is dedicated to Cellular Automata. However, instead of harnessing their complex behaviour, the objective is to reproduce the structural complexity of intricate patterns and motions observed, for example, in the nested patterns studied by Wolfram (2002; 57). In short, it can be assumed that the scope of application for a Cellular Automata model widens as space for nonlinearity and unpredictability in games is found. The examples presented below will reflect these three preliminary directions for applying the Cellular Automata model, namely visual, behavioural and structural.

4.5.1 *Open Worlds*

In line with the elements discussed above, modern large open-worlds similar to those observed in *Red Dead Redemption*, *Skyrim*, *Tomb Raider* and *Far Cry 3* would represent an ideal stage to implement the model of Cellular Automata. More specifically, the large maps contained in these titles, built on the principle of free exploration and nonlinear story progression, offer a promising setting to witness the development of Cellular Automata driven units on the visual, behavioural and structural levels. Due to large amounts of environmental elements present in open worlds, it becomes therefore possible to better exploit the complexity of Cellular Automata. When looking directly at Cellular Automata simulations, we have seen how their complexity can essentially be observed as clusters of individual units which move and display some form of behaviour in relation to the rules they obey. Furthermore, the emerging shapes, whether static, periodic, semi-periodic and/or travelling, often generate, after a number of generations, intricate patterns which can be interpreted as complex structural formations. In open worlds examples can be envisioned for Cellular Automata to display both their visual/behavioural characteristics as well as implement them as a source to generate structures which would directly affect the geography of the environment and constitute part of it.

At the structural level, open maps provide vast areas in which the intricate patterns displayed by Cellular Automata can be harnessed for a procedural generation of external and internal features of land structures. Therefore, by referring to the complex patterns shown by Cellular Automata after a certain number of time-steps, our model can feed to the GPU the values which will affect the morphology of geographical elements present on the map. The distribution and morphology of inanimate external structures such as terrain, rocky and deserted areas, and the level of thickness of forests and generally verdant sections, for example, can be generated in different configurations at each playthrough by implementing different Cellular Automata initial rules and/or starting formations. Further external inanimate environmental elements such as the formation and distribution of clouds and smoke caused by fires could also rely on the visual element generated by Cellular Automata model. More specifically, this could be made possible by utilizing a multiple background Cellular Automata simulations which reset their initial configuration/rules more frequently as to coincide with the in-game simulated day/night cycle and which activate in the presence of events causing smoke dispersion. Aside from the possibility of affecting the morphology of open-world external elements, also internal structures could present a different shape at each playthrough in response to the Cellular Automata model. More specifically, internal caves, which are regularly present in open worlds to serve several gameplay and story functions, would represent one such element which may each time appear in a different shape and therefore force players to adopt different approaches. In open worlds such as those from *Far Cry 3* and *Tomb Raider,* it is possible to discover several caves contained in the map. These caves, once navigated, present platforming challenges that often lead to the discovery of a hidden treasure, as in Tomb Raider. In other cases, as in Rook Island of *Far Cry 3*, they can also be used as hideouts to stash loot, stolen vehicles, and/or as an escape from enemy factions or a place to bait them. Similarly, caves and dungeons represent traditional map elements in RPG titles, which players can explore in order to defeat enemies and retrieve items. Therefore, it is possible to imagine how altering the internal structure of the caves can lead players and enemy AI to take a different approach to the combat and navigational gameplay sessions occurring within them. Likewise, a novel configuration of the external geography of the game map may lead to significant changes in the way players will carry out primary and secondary missions during a new campaign. Open worlds such as Rook Island are scattered with enemy camps which players can attack and liberate in an unspecified order and by adopting different strategies. The distribution of environmental features such as rocks, mountains, cliffs as well as vegetation assumes an important strategic function, since these can serve as tactical vantage points and hideouts for players to observe the movements inside the camp while remaining undetected. Furthermore, these geographical features become important also during combat and escaping sessions. Trees and rocks, for example, can provide cover, while steep mountainous paths or thick forests may offer useful escape routes. Varying map conditions generated by Cellular Automata would generate new combat settings, forcing players to embrace new tactics when liberating camps and conquering more territory, and enemy units to modify their behaviour to cope with the new environments.

Item distribution and growth dynamics could also be governed by Cellular Automata and offer important variations in terms of gameplay. For example, aside from controlling the position of objects such as crates, chests and/or buildings on the map, the Cellular Automata model could govern the growth and distribution of grass, trees and vegetation as well as the spreading of accidental and caused fires. This would not only offer unpredictable variations during gameplay, but would also eliminate the need for designers to manually insert every single item.

We have discussed how the way open worlds construct the narrative relies considerably on how players decide to approach the interactive possibilities offered by the environment and enemy/friendly AI and the events that follow such decisions. In this type of open, nonlinear context, the series and modes of actions taken by players and the responses from the virtual world and the AI-driven units constitute the personal narratives defined in the first chapter. In the light of the gameplay and narrative elements pertaining to open worlds as those discussed above, it can be imagined how the variation in the morphology of the geographical and environmental features of world map would have a significant impact on player’s personal narratives. Unlike what would happen in current games, where the map would be identical, at the start of each new campaign, players would encounter different map configurations and initial settings. This would lead to a variation in terms of strategies to adopt to overcome the game’s challenges and would force players to take different decisions and courses of actions. Given the nonlinear dynamical nature of Cellular Automata, small changes to the initial settings would ensure each new map to be unpredictably and drastically different from the previous one, essentially generating a new gaming experience once the game is restarted.

The elements explored above show the potential of Cellular Automata to bring structural unpredictability to the game environment and therefore render players' personal narrative in open worlds different during each new campaign.

However, Cellular Automata can also be employed in order to govern the behaviour of animate entities. Animate elements belonging to the flora and fauna of rural settings could represent in this case ideal candidates. For examples flocks of birds flying in formation as well as the collective behaviour of insects, also known as swarming, in certain locations of the map could be controlled by Cellular Automata. Indeed, the complex patterns shown by group dynamics such as flocks or other types of migrating animals could be reproduced autonomously through the CA system, not unlike Reynolds' Boids. Interesting complexities may indeed emerge by directing the population growth of animals inhabiting areas of the game world as well as vegetation implementing the original rules of the *Game of Life*. Vegetation, as described earlier, would display differences in terms of its properties and distribution and this would, in turn, have an impact upon the nature and series of events caused and encountered by players during gameplay. Furthermore, since its generally static configuration and more passive function would make it more compatible with the game environment and gameplay mechanics, it could extend across the entire map in a nondisruptive fashion while maintaining complexity and unpredictability. However, when we turn our attention towards animate and moving entities such as populations of wildlife animals, it becomes important to consider their potential invasiveness in the light of the unpredictable evolutionary path dictated by the Cellular Automata model. An initial use of Cellular Automata to govern animate agents which move and change their position on the map could benefit from the concept of the zoo scenario discussed above. This would involve dedicating specific territories on the map for the game units in question to develop. These areas would need to be both reachable by the observer/player and separated from other areas of the map where events fundamental to the progression of the game need to occur. While open worlds give ample space to players to explore and interact with the game world at a pace and mode of their preference, carrying out several secondary missions and discovering scattered narrative fragments, the progression of the campaign is still reliant on certain mandatory checkpoints. These are represented, and often highlighted in the menu, by primary missions whose completion allows players to from the beginning to the ending of the major story arc and complete the game. By randomly scattering Cellular Automata population across the entire map, situations may arise (explosive growth) in which players are no longer able to reach key locations and/or accomplish missions in order to progress. Therefore, an initial containment of Cellular Automata populations would be necessary to ensure a flowing gaming experience. While the structural complexity of Cellular Automata can play an active role in the gameplay and impact the way players approach each mission, the behavioural complexity of animate agents may at first assume a more passive, observable role. Cellular Automata driven entities could populate the sky and the waters, adding to the realism of the environment, or be placed, as in the case of Rook Island in *Far Cry 3* or the Yamatai Island in *Tomb Raider*, on separated islands which players could visit in order to observe how they are evolving.

However, in order to inject unpredictability in the main story events, these populations could be allowed to interact directly with the players and the main map’s environments upon the start of a second campaign. Enemy and neutral animal populations, such as the tapirs, hyenas, dingoes and wild boars in Rook Island, or the wolves in Yamatai Island, could develop following multiple Cellular Automata simulations whose grid is represented by the entirety of the game map. The survival behaviour and reproductive phenomena observed in the *Game of Life* could then arise in the game environment leading to outcomes whose unpredictability would be enhanced by perturbation variables such as the input received by the environment and the interactions with the player. During navigation and gameplay, players may face and adapt to novel situations not previously encountered. In the internal regions of the Yamatai Island, for example, it is possible to encounter packs of wolves who are scripted to attack the player on sight. Upon seeing the player, their state changes from roaming to attack, with the latter consisting of the following scripted actions: bite->create distance->flank->bite. Unlike what can be observed in real life, wolves do not perform group attacks in this case, and their pack does not contain more than three units. Once players have memorized their action cycle, they can defeat each wolf with ease. Instead, by introducing a Cellular Automata driven collective behaviour, it would not be possible for players to predict how many wolves may be around and how they would react to the player’s presence. Furthermore, in case of an attack, players would not be able to anticipate when this may happen (not necessarily at first sight) and how this will be carried out (individually, collectively, in small groups etc.). Players may then prefer to stay clear of certain areas or, in case these need to be traversed in order to accomplish a mission, they would need to carefully observe the wolves’ behaviour to then devise and test effective strategies to overcome this type of obstacle. However, since Cellular Automata behaviour can change drastically with minimal perturbations, players would not be able to rely on any type of behaviour repetitiveness, and would need to be ready for unpredictable scenarios. Similar situations may also arise independently among Cellular Automata animal populations interacting with each other and with other NPCs present in the game world.

By combining the visual, structural and behavioural phenomena of the Cellular Automata model, it becomes possible to introduce several elements of unpredictability upon the start of each new campaign. In the sandbox genre, open maps allow for Cellular Automata complexity and emergent behaviour to arise and be subject to interactions with players and NPCs. The resulting unpredictability directly affects the personal narratives, which are a prominent feature of the genre, by rendering them nondeterministic.

4.5.2 *Simulations and God Games*

The previous examples have suggested a number of ways to apply the Cellular Automata model to open worlds. In this genre, players navigate and interact with the game world in a direct way, normally by controlling of one or more avatars from a third or first person perspective. Since the gameplay relies on an immediate type of interaction with the game world, the implementation of Cellular Automata in this genre would therefore manifest at a visual and structural level primarily in order to be extended to the entire map. The behavioural unpredictability would involve units initially relegated to confined spaces.

However, genres such as simulations and god games, where players have a general control of several resource elements concerning a wide variety of complex systems such as populations, cities, countries, restaurants and so on, may provide fertile ground for experimenting and testing the emergent complex behaviour displayed by Cellular Automata.

In urban settings such as those observed in city simulations like the latest *SimCity* edition (Maxis, 2013), for example, players need to manage the development and welfare of one or more cities. Each city can be viewed as a larger system consisting of a varying number of sub-systems, each developing in accordance with specific variables that are particular to that system and/or are generated through the interaction with the other sub-systems. The overall success of a campaign consists of expanding the main city while preventing the failure of the sub-systems and preserving a positive developmental line for these. The large number of variables dictating the behaviour of each system, along with pre-established scenarios, ensures a frequent occurrence of problems requiring players to intervene in order to solve them and re-establish positive parameters for the general development of the city.

As indicated in the first chapter, the complexity of simulation and resource management games emerges primarily from the large number of variables present in each system. However, the way these variables affect the system, the types of interactions between systems and the way these respond to the player's input are reliant on a finite state machine logic and therefore finite in nature, with repetitiveness of scenarios as an inevitable outcome. Furthermore, due to limited computing resources as well as the objective of representing an abstraction of the city, rather than re-creating it in its entirety, some elements such as pedestrian and traffic flow, weather system and citizens' daily activities still respond to scripted algorithms, while other systems may be entirely absent. It is among the sub-systems composing the city that Cellular Automata could be employed. For example, traffic flow could be configured according to Cellular Automata simulation, borrowing also from the Maerivoet and De Moor's CA modeling of traffic dynamics (2005). Similarly, the collective behaviour of local and non-local citizens during public events (i.e. Christmas Sales, sports events, university open days, music concerts, weekend nightlife etc…) could respond to the Cellular Automata model, thus influencing other minor and major sub-systems such as public transportation, road traffic as well as economy and house pricing. To add to the behavioural unpredictability of these in-game entities, the Cellular Automata model could also be applied to more specific settings such as sanitation and health care. More specifically, the distribution dynamics of virus outbreaks and pandemics in populated urban settings may be governed by Cellular Automata. These three scenarios of Cellular Automata application to a city simulator setting serve as an example of how to harness the unpredictability generated by emergent behaviour. Since cities constitute semiautonomous system, and therefore require input from the player, using Cellular Automata along the lines suggested above would create novel situations for both the game system and the player to be engaged with. Each city would therefore offer unpredictable events which would be different in each new campaign and/or during the course of the same campaign. This is especially true when we consider inter-connection among all the sub-systems which makes their individual development dependent on each other.

Similarly, army and war simulators are also suitable genres where the collective behaviour of single units can be governed by the Cellular Automata model. In real-time strategy simulators like the *Total War* series, for example, battle and invading scenarios during the Roman expansion constitute core gameplay elements, with the player commanding his or her own army and the enemy AI responding accordingly through higher and lower level strategic decisions. With the combination of certain variables and conditions, the enemy armies will carry out specific actions, making these predictable after a certain amount of time spent observing the several reactions. By applying Cellular Automata to guide the behaviour of enemy and friendly/neutral allies during battles, it would be possible to prevent repetitiveness, and players would be forced to constantly re-adapt their strategies in the light of unpredictable, yet possibly complex behaviour from the AI. Armies governed by Cellular Automata may, for example, devise survival strategies which may manifest themselves in a variety of outcomes and may not be easy to predict. Input from players would cause a perturbation to the system governing the enemy army and trigger major changes which would differ greatly with different variables and conditions. Since the playability of titles belonging to this genre is centered around live battles, it would be important for designers to carry out extensive testing of Cellular Automata responses to different types of inputs across a wide range of conditions in order to maintain initial conditions and rules leading to positive results and exclude game-disrupting configurations.

Finally, another promising game world setting whose principle could be exploited for Cellular Automata populations can be observed in a game typology knows as god games, such as the galactic civilization simulator *Spore* (Maxis, 2008). The game proposes an entertaining version of the evolution of life, from microscopic one-cell organisms in the primordial soup to complex land and water animals and finally intelligent species capable of social, cultural and technological expressions. Featuring a similar “god” gameplay as in *The*

Sims, *Spore* allows players to develop and manage their own species on a predetermined path to intelligence, selecting their home planet and initial biological profiles.

Once the player's civilization reaches the space stage, it becomes possible to travel to other planets and interacts with other species. However, the species encountered are few, they have developed according to pre-established parameters rather than through a random or autonomous process, and only a limited number of planets offer this possibility. Cellular Automata could, in this case, offer randomization of species across the planets, with their development and evolution occurring in direct correlation with the features of their home planet. Upon visiting the planet home to the Cellular Automata population, players, as well as designers, would not be able to predict what they will find. According to the type of initial conditions and rules enforced during a particular campaign, Cellular Automata may have developed into stable or periodic localized formations in a finite region of space, may travel across the planet in small clusters or display unbounded growth or may propagate and reproduce. Similarly, players may find the planet barren of game entities, as these may have disappeared sometime after the start of the game.

A final interesting addition to this scenario would be to introduce a second population of Cellular Automata on the same planet, following along general lines the models of predator-prey dynamics (Edelstein-Keshet, 1988) and Renning's modeling of HIV virus spread countered by antriretroviral agents (2000). One interesting game scenario would emerge, for example, with population A developing defense and survival mechanism against population B.

A similar principle could be used in turn or real-time strategy settings, with selected civilizations growing in a Cellular Automata framework. More specifically, rather than translating directly into visual and physical counterparts, the evolution of Cellular Automata could be used as a model to control developmental variables of certain civilizations, such as economy for example.

An important factor to be considered and which applies equally to the god game genre, is whether players are able to interact directly with the game entities controlled by CA and understand how this will affect the narrative of the game. We have seen how unpredictable CA systems can be introduced in the game world in confined locations of the map. In settings similar to those found in Spore, Cellular Automata population develop on separate planets in distant star systems, and are therefore isolated from the main gameplay areas. These separated territories will be the stage for nondeterministic chain of events, therefore nondeterministic narratives players can witness as external observers. The non-determinism and lack of pre-established control will emerge through different outcomes at every new campaign. Certainly there is potential for interesting events to emerge if players are allowed to interact by intervening in real-time on the Cellular Automata simulation. The results of these interactions, however, are currently unknown, and cannot be predicted. Intervening in real-time on Cellular Automata models like the *Game of Life* represents a type of perturbations which can significantly affect the evolutionary trajectory. By arbitrarily adding, for example, live cells in an on-going simulation, the CA population may integrate the new cell, cancel itself entirely after a few steps or grow exponentially eventually occupying all available squares on the grid. Other more complex reactions are also possible, and this constitutes a strong experimental motivation. Likewise, in a game environment, direct interaction may render the game unplayable, for example, if CA-driven units invade the entire available map, forcing players to abandon the current campaign. Similarly, units may carry out inexplicable actions and behaviours, and may display complexities of various forms which may not necessarily bear a logical credibility from a human point of view. Yet, it cannot be excluded that in the presence of certain conditions, complex and seemingly intelligent responses may be observed and enrich the game experience. Responses, regardless of their nature, may happen only once. It will ultimately depend on the player to decide whether to observe or intervene, experiencing direct and irreversible consequences. The crucial element is not being able to predict, and this may represent a promising starting point to address the deterministic nature of video game narrative structures.

4.5.3 ***2-D Side Scrollers***

The scenarios discussed above are derived from modern design based on large three dimensional maps which can be navigated in a continuous fashion or be observed in their entirety from top-down perspective. The size and rich interactivity offered by these environments provide ample opportunities for experimenting with the effects of the Cellular Automata model on the visual and structural level for what concerns the environment, and on the behavioural level involving NPCs. As we have seen, in open world maps such as

Rook Island in *Far Cry 3,* all three types of Cellular Automata complexities can be exploited at once, while more emphasis can be placed on behaviour in simulators, and god/real-time strategy games. However, also returning to a more traditional 2-D game design may constitute a suitable stage for experimenting with the Cellular Automata model. An important reason derives from the large number of indie developers embracing this type of game design due to the less complex and lengthy development process involved, as well as a higher degree of design freedom due to less commercial pressure and smaller development teams. This may lead to a strong interest in experimenting with innovative design and gameplay features and less concern regarding the unpredictable effects generated, for example, by the Cellular Automata model.

One prominent genre in 2D design, namely the side-scroller, would open the possibilities of harnessing the visual and behavioural complexities of Cellular Automata. In side-scroller games players are normally presented with a two-dimensional game world from a side-view perspective or a top-down angle. The boundaries of the game world are represented by the edges of the screen, and more of the map is revealed as players proceed in a horizontal or vertical direction. Unlike the examples proposed for sophisticated 3D titles, where the Cellular Automata simulation operates as a background and invisible process and is translated into 3D structures as well as behavioural traits, in side-scrollers the patterns and motions of clusters of Cellular Automata would closely resemble the two dimensional formations observed in the *Game of Life* as well as Wolfram's 256 rules. The feedback of the background simulation would be more direct, proposing the same type of formations (i.e. gliders, puffer trains, methuselah etc…). In the case of static patterns, they would appear on the screen in the form of obstacles to avoid or traverse, while moving clusters may represent enemies to defeat or avoid. The several different configurations of moving clusters observed in the Life Lexicon could represent enemy entities in side-scroller shooters, while the complicated static figures studied by Wolfram, such as rule 110, or rule 30, may serve as two-dimensional mazes and structures to traverse in platformer titles similar to the *Castlevania* and *Super Mario Bros*. series. Testing would be needed to prevent the formation of closed or impassable patterns. Additionally, a simple algorithm may be introduced to detect in the evolution of a given Cellular Automata configuration structures which can be traversed and are compatible with the gameplay. The evolutionary trajectory may therefore be halted at that specific generation to make it available for gameplay.

In this type of scenario, Cellular Automata would constitute a primary gameplay element, presenting players with a variety of unpredictable and complex structures/enemies to overcome. Due to the nature of the genre, this would apply to every gameplay session during a given campaign.

4.6 Future Work: Genre and Rule Selection

In the previous examples some of the possible scenarios in present day game design have been explored in order to understand where and how the Cellular Automata could be implemented. Aside from illustrating how nonlinearity and unpredictability of Cellular Automata may translate in terms of gameplay and game world interactions, they may also serve as a starting point for designers interested in developing future titles designed primarily to take advantage of Cellular Automata. When looking at a prototypical title indicative of what future work may concentrate on, important factors such as rule selection, testing and genre need to be considered.

It has been indicated how the traditional gameplay architectures which lie at the basis of games' successful formula require a careful integration aimed at creating pockets of complexity without disrupting the gameplay experience. Due to the wide variety of outcomes displayed by Cellular Automata simulations, as well as the difficulty in creating shortcuts to predict them beforehand, extensive testing would therefore represent a crucial step to safely integrate the technology into the medium. This would allow the arbitrariness and randomization selection of Cellular Automata initial conditions to be narrowed down to rules and configurations which are compatible with a specific genre and predisposed to generate complexity and unpredictability while still preserving playability for the user. It has been discussed how one immediate effect of the Cellular Automata model is that of making new scenarios and situations available and, as a result, constantly altering the series of events constituting players' personal narratives during gameplay. The flow of (gameplay) events no longer relies on designers' pre-established scripts, but it is rather generated in real-time according to the nonlinear dynamics of the Cellular Automata system running as a background process, and is therefore non-deterministic and unpredictable without being stochastic.

We have observed how the degree with which the model can impact the narrative structures varies according to the type of genre in which it is being implemented. While more linear and story-driven games may provide only small pockets for non-determinism through Cellular Automata, other genres such as sandbox/open worlds, simulations and god games appear to be more suitable to a non-deterministic overall narrative arc due to the absence of a pre-established story direction. Among the genres which favour the application of Cellular Automata, a simulation game based on resource management and the development of several interconnected systems, such as a city simulator, would greatly benefit from the implementation of a Cellular Automata framework. One primary reason is represented by the very modular structure of *SimCity*-like simulations, in which the overall status of the super-system (i.e. farm, city, nation or empire) is constantly updated through a time-step process similar to Cellular Automata and is determined by the combined values of the various sub-systems which serve as the fundamental blocks of the simulation. The potential of this type of modular and system-based architecture lies in the possibility of integrating multiple Cellular Automata processes in order to allow each individual system to run and behave according to its corresponding simulation. One additional factor centering the use of Cellular Automata on this genre is represented by the general openendedness of the single player campaign. If in linear as well as sandbox titles a primary story arc can be identified which determines all the intermediate phases of the game's progression, this is relegated to a secondary and decorative role in simulations of systems. In games like *SimCity* players progress through a number of customizable tasks which are aimed at revealing all important details regarding the sub-systems (i.e. citizens' happiness, economy, employment figures). Rather than following a pre-determined story path, these tasks serve as a tutorial for players to learn how to better ensure the general wellfunctioning of the super-system in question. Once players have gained an understanding of the several systems to manage, it becomes possible to build cities in several customizable scenarios and observe how these develop under different conditions, without introductory, intermediate and ending cutscenes. The events occurring during gameplay depend on the variables generated by the interactions between the sub-systems and through the player's interventions in order to manage them. This open-ended computer-generated narrative, along with the absence of story checkpoints, makes this genre an ideal first candidate for a non-deterministic design upon which future work might be based.

4.6.1 *Hardware setup*

Before discussing how to implement the non-deterministic models at the software level in a game prototype specifically designed within a Cellular Automata framework, it is important to understand what type of hardware setup may be needed among developers as well as target gamers. It is fairly reasonable to assume that a successful integration of Cellular Automata in game design may lead to the development of titles available for all gaming platforms available.

However, it must be reminded that modern games are initially developed on a PC environment due to the higher amount of computing resources and flexibility offered by the computer. Once the fundamental components have been developed and tested through the alpha and beta phases, the game is then optimized and made compatible with other platforms. Therefore, future development on a prototypical city simulator based on Cellular Automata would require a PC hardware environment with high specifications for its initial design, with the final product being fine-tuned and re-adjusted to match the computer specifications of the average user.

Since the objective is to build a complex AI architecture containing multiple Cellular Automata simulations dedicated to each of the game's sub-system and running calculations simultaneously, a strong multi-core processing framework would be necessary. The various Cellular Automata simulations would be distributed among the several cores contained in the CPU, with the values relative to each sub-system being updated in real-time and fed as combined values to the GPU architecture for graphics rendering.

A prototype Cellular Automata-based city simulator would be very CPU intensive. On the other hand, the configuration of the graphics compartment would depend on the level of detail and elements appearing at any one time on the screen. City simulators normally offer a top down view of the city, with players being able to control the camera and zoom in until street level. While the level of detail may determine the workload of the GPU, the map size would not be larger than current open world titles which are comfortably rendered by modern mid or high-range graphics cards. Furthermore, also adding extra levels of details and large numbers of simultaneous visual elements for the prototype in question would be possible with more powerful GPUs capable of rendering 150 billion texels per second (with one texel representing the unit component of a texture).

Understanding what type of hardware configuration is a necessary step for future (independent or team) developers willing to implement Cellular Automata in their game AI architecture. It is a logical step to take prior to discussing how to implement Cellular Automata at a software and gameplay level. What emerges from the above observations is that running multiple simulations based on the binary data of two-dimensional Cellular Automata as background processes would require designers to work on a CPU intensive developing environment, ensuring that ample resources in the form of numerical data are dedicated to each of the sub-systems composing the super-system, in our case the city, that players will manage.

4.6.2 *Software implementation: prototype, testing and optimization*

Once the hardware environment for a prototype has been established, as well as the game genre and type of gameplay players will experience, it is possible to start exploring the related software implementation and its direct effects on the gameplay and in the game world. As indicated earlier, the software implementation phase has the ultimate objective of coding, testing and optimizing a computer program based on two-dimensional elementary Cellular Automata within the prototype city simulator AI architecture. It has been mentioned how this program can be based on the configuration of Conway's *Game of Life*, consisting of a two-dimensional squared grid in which two-state (dead/alive) automata expand and evolve by interacting with their neighbours according to an initial set of rules. In order to add to the variety of the possible evolving scenarios, the initial rules can be customized and expanded beyond Conway's setup, described in the third chapter, by referring to the 256 possibilities studied by Wolfram. Another customizable element is represented by the number and position of active automata at the start of the simulation. The computer program will then have the task to exert a specific influence on the game's sub-systems by running multiple simultaneous simulations according to the number of entities chosen to be governed by Cellular Automata.

Establishing a Cellular Automata framework by coding an apposite computer program distributing the several simulations across the cores and coordinating them with the game’s visual and numerical output represents the first phase in the line of development. In this stage, a prototype is built and made stable for a computer program based on a customized version of the *Game of Life*. This is an essential first step paving the way for the extensive testing phase which follows. The main objective of the second stage is to test how the game’s sub-systems and super-system behave as they respond to the background Cellular Automata simulations. The aim is to create a balance between the potential unpredictability and complexity emerging from Cellular Automata and the need to maintain playability during gameplay, discarding configurations which may prove disruptive and bring the game’s functioning to a halt and preserving those with a higher degree of compatibility. Ideally, the testing phase would operate across three levels. Each sub-system would initially be tested in isolation in order to observe how it evolves autonomously. This would allow for the identification of configurations which generate positive evolving scenarios. The interactive phase would then ensue as these configurations are subjected to a variety of external inputs in order to observe how perturbations may affect the sub-system. In a twodimensional Cellular Automata framework, external input may come in the form of adding or removing individual automata per time-step. In gameplay terms, this may translate into players adding or eliminating game entities which are part of a specific system. For a Cellular Automata sub-system controlling population growth, habitation or vegetation distribution, for example, players may be allowed to add or remove houses or forest patches. It may also be possible to connect the city to other nearby cities by land, air or water, promoting the affluence of outside citizens which may add to the existing population. Another scenario may arise in which players change the configuration of the road network, which would in turn affect the traffic flow. All these types of player’s interventions would affect the computer program by adding or removing individual units in the Cellular Automata population. It would therefore be important for designers to test how each subsystem responds to this type of input to further refine the selection of suitable configurations. A third testing phase would then follow with each sub-system being run in conjunction with other sub-systems in an incremental way, in order to observe the chain of events caused by their interaction with each other and with the player.

Once extensive testing is carried out, it is possible to enter the final phase in which the Cellular Automata program is further stabilized and optimized. This final process heavily relies on the results yielded by the testing phase. More specifically, the final optimization of the program will take into account two crucial factors emerging from testing. The first factor is represented by observations regarding the way the program makes use of the available computer resources and how this affects the overall in-game performance. Understanding how much computing resources the program takes will allow developers, for example, to increase or decrease the number of simultaneous simulations in order to ensure a smooth performance of the game. The second factor emerging from testing is represented by the identification of Cellular Automata configurations which are compatible with the game structure and ensure continuous gameplay. This awareness will enable developers to optimize the program to draw from a pool of compatible configurations at each new campaign.

4.6.3 ***Software Implementation: Gameplay***

The more technical integration phases of prototype, testing and optimization do not occur in isolation, but are paralleled by the selection of which sub-systems may be more suitable for the non-deterministic architecture of Cellular Automata. It has been established that in our simulator prototype, the city represents the super-system whose functioning is determined by the interaction of a number of interconnected sub-systems.

The gameplay scenarios observed above for current games may serve as an ideal starting point. More specifically, it has been explained how Cellular Automata can exert visual/structural and behavioural influences on the game entities. All three types of properties could also be included in the systems of the city simulator to ideally exert their influence from external systems such as weather, geographical landscape, wind and water dynamics to internal city-related systems such as traffic/pedestrian flow, economy, health care, employment system, crime and law enforcement and so on. The target is to enable an autonomous micro-world where each component is a dynamical system that develops and changes over time according to its internal mechanics, by being affected by the other systems and by affecting them. The internal dynamics of each system are governed by their correspondent background Cellular Automata simulation, with the city itself becoming a nonlinear dynamical super-system with which players can interact.

There are two categories of sub-systems which can behave responding to the Cellular Automata program. The first category includes systems which can be considered external to the city itself, and are represented by the natural features of the geographical landscape upon which players will choose to build their city. Following the tradition of city simulators, at the beginning of a campaign, the entire world map is provided to players in the form a small globe in order to select a patch of land where the city will be built. The physical features of the world map can appear different at every campaign and be determined by the program. The land geography, complete with mountain ranges, valleys, river networks, vegetation and desertic areas will therefore differ in landmass and continental distribution every time players initiate a new campaign. Similarly, the distribution of the water mass of the planet will also be subject to different configurations, and features such as fractal geometry may emerge. This type of geographical variation represents a crucial factor for a non-deterministic gameplay as it would force players to cope with different environmental conditions and affect the harvesting of land and water energy resources which is essential to the development of a urban settlement. According to the computing resources available, more natural sub-systems could be added such as weather dynamics, flora and fauna growth and distribution, tectonic drift as well as water and ocean dynamics. It is easy to imagine how the nonlinear functioning of these natural systems and their high sensitivity to small perturbations may have a considerable impact both in the short and long-term, affecting, for example, the economy, development and safety of the player’s settlements. In an agriculture-based economy, for example, the weather system and the distribution of natural resources and cultivable land would play a central role, as players would need to adapt to and best exploit the climate conditions of the chosen areas. Similarly, the development and welfare of fishing-based settlements would be affected by the water dynamics and the distribution of fish life, which would in turn also be affected by other natural systems, such as the weather and climate warming, or internal systems built by the player such as industrial compounds and related phenomena like air and water pollution.

Also modern industrial cities may be affected by the dynamics of the natural systems, with extremes of weather causing problems like delays and jams to the transportation system, road traffic, and in turn affecting all the interconnected sub-systems by various chains of events. It may be possible, for example, to imagine how extreme phenomena like draughts or floods, induced by unseen chains of events (ice melting, climate change, desertification, deforestation and so on) resulting from the underlying nonlinear dynamics and players' inputs, may cause critical damage to the city's infrastructure, compromising a number of systems and requiring players to intervene with contingency plans. Similarly, other CA driven physical systems such as tectonic drifting and volcanic activity would also be likely to cause long-term events such as sudden earthquakes and/or eruptions, whose magnitude, location and time would be unpredictable.

With the player's role as being that of maintaining an overall positive functioning of the city by observing the development and status of each system and using a range of tools to intervene in case of problems and malfunctioning, it is possible to imagine how nondeterministic chains of events occurring through the influence exerted by these CA driven natural systems upon the settlement would require players to constantly cope with new and unforeseen situations. Even ensuring the best possible conditions, small perturbations caused by players or the city systems would have invisible repercussions and preserve a constant state of alert.

Aside from external systems capable of affecting the player's settlements, also a number of systems internal to the city could be controlled by the Cellular Automata program. Ideally, as mentioned above, the internal systems should be capable of affecting each other and influence the overall status of the city. We have already mentioned how systems such as road traffic, pedestrian flow and transportation infrastructures could be included in the internal Cellular Automata sub-systems. These systems could in turn be influenced by other Cellular Automata sub-systems such as economy, education and rate of employment. Phenomena such as traffic jams may arise during rush hours, with players trying to optimize the traffic flow by adding or modifying the road network. High employment rates and education opportunities may lead to a thriving economy and attract people from nearby settlement, affecting, for example, the prices and distribution of the housing infrastructure influenced by population growth and expansion. Players may also observe overcrowding phenomena during weekends and during seasonal sales and city festivals. However, the nonlinearity of phenomena such as road traffic, pedestrian flow and population growth may lead to unexpected scenarios requiring players to maintain a constant degree of attention in order to preserve the city's functioning status. Finally, the predator-prey dynamics modelled through Cellular Automata and discussed in the third chapter as well as fire spreading patterns described earlier in this chapter could provide further opportunities for application. More specifically, three sub-systems could be added which may increase the number of in-game unpredictable scenarios and may also have an impact upon the population. These are represented by the threat from a number of viral pandemics along with their rate and mode of infection across the population, accidental domestic and urban fires and their distribution and finally the spread of criminality. Unexpected events which may emerge from these three sub-systems would all require containment measures to be enacted by three correspondent counter-systems together with the help of the player. For example, viral epidemics would require a response from the health system to effectively deal with the threat. Devising a cure and/or manufacturing a vaccine with the help of players (i.e. by giving more funds to scientific research) would be vital to the wellfunctioning of the city and would help avoid a serious crisis among the population. Similarly, accidental fires would require an effective intervention from the fire brigade system in order to avoid the spread to uncontrollable levels. Finally, the system controlling the criminal activity may generate several events such as theft, murder, drug dealing and gangster related activities and be directly affected by the levels of wealth and economy as well as the efficacy of security forces in containing it.

In this type of city simulator scenario, where a number of external and internal systems are governed by the nonlinear dynamics of Cellular Automata, the unpredictability of behaviour of one system can virtually affect all the other systems, increasing the number of possible situations which can arise and eliminating repetition not through randomness or chance, but through nonlinearity. Furthermore, the possibility for players to interact with the city's systems (and therefore cause perturbations), which leads to significant alterations to the system's trajectory over time, makes every single decision have both short and longterm effects on the overall status of the city. The intricate causative network generated by the consequential ramifications of the several systems towards each other would make the series of events, and therefore the narrative pertaining to the development and growth of every city, unique and non-repeatable for each new campaign. The nonlinearity and complexity of each system, based on its corresponding Cellular Automata simulation, would give rise to a non-deterministic narrative structure rich with spontaneous, rather than pre-established, events. The interconnectedness of the several nonlinear dynamical systems driven by the Cellular Automata program would ensure a non-deterministic flow of events characterized by unpredictable scenarios

The absence of a script and the autonomous generation of events would also eliminate the need to impose specific difficulty settings, since the nature of the events which will occur in each campaign will simply be unknown prior to the start.

Chapter 5. Conclusion

5.1 Addressing the Problem of Determinism in Game Narrative Structures

The research presented in this study has developed around the following question: given the current state of video game narrative structures, is it possible to address their deterministic nature in order to create a non-deterministic architecture? The answer, which is elaborated in the final chapter, describes the application of a nonlinear dynamical model based on Cellular Automata to the game AI in order to generate a non-deterministic narrative and gameplay framework.

In order to identify a non-deterministic model applicable to video games capable of affecting the nature of in-game events, the study has approached the research question by focusing on three central key areas:

1) Nature and history of the medium and the meaning, function and importance of narrative within it

2) Definition and various implications of determinism from a philosophical and scientific perspective

3) Identification of several types of non-deterministic systems (markovian, stochastic, nonlinear) and selection of a specific nonlinear dynamical system (Cellular Automata) as a candidate to address the determinism of video game narratives. A Cellular Automata model is developed for integration in game design

5.1.1 *Categorization of Narrative Structures and Dependency on Game AI*

In the first phase of the study the aim has been to bring clarity regarding the definition, role and implementation of narrative throughout the history and development of video games themselves. This has been possible only after identifying and outlining the fundamental components that constitute the nature of the medium in spite of the rich diversity of styles, themes, purposes and modes of interactions which can nowadays be observed. With a clearer concept of what the game medium is and the features that distinguish it from other forms of media, it then became possible to gain a better picture of the role of storytelling in game design and how it evolved throughout the medium's history. Identifying the core components of video games has revealed two important aspects of narrative as seen in this context.

The first aspect is represented by the close link which exists between narrative and the *mimesis* or role play element which is fundamental to the gameplay experience. The alternative version of reality offered by video games requires players to temporarily assume an alternative identity, be it an athlete, an astronaut, a tennis player, a city major or a soldier, by adopting a different persona during gameplay. This role play element holds true even in titles which are not story-driven, such as sports or simulations, and can be found among the very first games such as *Spacewar!* and *Pong*, indicating how the narrative element, while not always prominent, constitutes an inseparable component in the design process and gameplay experience.

The second aspect regards the adaptation of the notion and traditional definitions of narrative in the video game context, where the interaction between the player (narratee) and the game world created by the designer (narrator) plays a fundamental role in the unfolding of the events (narration). This collaborative act of narration between player and designer occurs in real time as players progress through the game by interacting with the game world. Establishing the presence of narrative as a core element in video games, and identifying the form its traditional elements take during gameplay set the premise for a more in-depth investigation of the various narrative structures used by designers and made possible by the medium to deliver the story content.

Furthermore, it has been shown how the importance placed on the narrative element in the design process has steadily increased. With the exception of adventure computer games, which were built as narrative experiences already during the late 1970s, the storytelling component gradually became central to the mass video game design process particularly after the implementation of 3D graphics, as its role shifted from decorative beginnings to an essential cohesive device to give meaning to and bind large virtual worlds together and a motivating factor for players' engagement and immersion in the game world. This increase of importance of the narrative component has led to the refinement and consolidation of several narrative techniques which not only reveal the medium's storytelling capabilities but also, essentially, shed light on its limitations.

The investigation conducted in this study, based on observations made on a large number of game titles covering all genres and spanning the entire historical development arc, has led to the identification of four fundamental narrative structures which define the medium's storytelling boundaries. Indeed, it can be argued that the first major contribution of this research lies in the first systematic categorization of four possible storytelling architectures which can be achieved by the medium and which are represented by pre-established, discovery, sandbox and computer-generated narratives. By understanding and explaining the properties of each of the four types of structures, two important factors emerge which are essential to finding a solution to the research questions. More specifically, it has been observed how all narrative structures operate within a deterministic and finite framework dictated by the in-game AI which has an essential role in the functioning of the game's narrative architectures. From the more linear scripted pre-established narratives, where the order and timing of the events stays unchanged, to the discovery type of gameplay in which more freedom is given to player in terms of how many/which story elements to retrieve, all content is pre-designed and events are finite and unchanging. Similarly, in sandbox and simulation titles where the narrative relies primarily on the events generated through the interaction with the game world and its NPCs, the finite and pre-determined types of behaviour which NPCs and environmental elements display leads to an inevitable repetition of identical events.

Emerging from the analysis is the awareness that, despite its diversity, the storytelling is still confined to finite boundaries, since all the events that can and will happen in the game through the interaction between the players and the game AI are ultimately pre-determined beforehand. In short, designers are able to predict which events will occur under which circumstances. In cases where stochastic or probabilistic AI techniques are employed, they would contribute to randomize only the order rather than the nature of the events.

Findings from the first phase of the study fill the gap in the existing literature approaching video games from a narrativist perspective, where accurate investigations of the narrative structures were generally incomplete, outdated and confusing at times. Furthermore, the close link emerging from the analysis between narrative and game AI reveals the unavoidable pre-determined spectrum in which game narratives operate. Despite the illusion of player's agency and the occasionally randomized variety, game narratives are still implemented through a highly controlled environment guided by deterministic AI architectures.

5.1.2 *Implications of Determinism for the Gaming Experience*

Despite the conclusion that all game narrative structures are deterministic, it is by carrying out a close observation of the game AI as the basis for all events occurring during gameplay that it is possible to find an angle of approach from whence to address and break the deterministic mechanism of video games.

This angle of approach characterizes the second phase of the study, in which the notion of determinism is explored from an historical, philosophical and scientific perspective and is followed by an investigation of the types of systems found in nature which bear deterministic and non-deterministic properties. Understanding the implications of a deterministic reality for humankind also contributes to revealing the fundamental and ultimate limit of video games in their current state. More specifically, the absence of free will, seen as a consequence of a deterministic universe whose future states can be predicted by knowing the past and present conditions, re-emerges in the virtual reality depicted in video games as the lack of true agency and real consequences for players' actions. It has been shown how game worlds are deterministic systems in which the future states of all entities, both player-controlled and computer-controlled, can be predicted. Therefore, the types of actions and decisions players can take during gameplay are pre-determined by the designer to follow specific interactive rules, as are the consequences deriving from players' actions. In this view, players are not truly responsible for the events occurring during gameplay and the playing experience becomes a set piece carefully designed by developers to promote entertainment and provide the illusion of agency. It has also been shown how the finite-state-machine logic governing AI in video games is modelled after the behaviour of systems observed in the physical world whose states can be predicted with a high degree of accuracy. Therefore, the objective of the second part of the research has been to identify and describe systems which do not follow a deterministic evolutionary trajectory but are subject to different types of unpredictability. In this context, it has been important to distinguish between probabilistic systems, such as markovian and stochastic systems, and nonlinear dynamical systems. In the case of the former, the nature of the future states is known, and only the transition to the next state is subject to probability. It has been explained how probability is also employed in game design in order to minimize repetition. This can be considered as a weaker type of non-determinism which, in the long run and in the case of games, eventually does not appear to significantly differ from the toss of a coin. If the result of being head or tail is unknown, both possibilities are known in advance and will not create unpredictable outcomes.

The search for a non-deterministic scenario in which the very nature of events, rather than the order, is unknown to both players and designers, therefore leads to consider the properties of chaos and complexity from nonlinear dynamical systems as elements to incorporate in game AI in order to inject stronger behavioural unpredictability leading narrative events that never repeat themselves. These properties are finally observed more closely in Cellular

Automata, identified by this study as a gateway to transfer evolutionary deviations caused by minimal changes to initial conditions, perturbations and internal interactions of the constituting elements into video games.

5.1.3 *Identification and Implementation of Cellular Automata in Game Design*

The final part of the study is dedicated to the explanation of how the configuration and simplicity of two-dimensional Cellular Automata simulations explored through Conway's

Game of Life can make the nonlinear system compatible with current game AI architectures. This represents the second major contribution brought by this research, which takes the form of the development of a model which applies the nonlinear properties of Cellular Automata directly to interactive and non-interactive elements of the game world. Examples of implementation are provided both for the current state of game design and for future development work.

5.2 Strength and Weaknesses of the Research

The attempt made in this study to address the determinism of game narrative structures has tried to keep speculation to a minimum, maintaining a realistic and updated view of the game industry and the medium's technological limits. Focus has been given to what can be actually done to innovate game narratives with the game technology at our disposal, rather than what we wish could be done in an unspecified future.

This grounded stance can certainly represent a strength, especially when compared to investigations made by previous content-based narrativist approaches which are hindered by a limited technical knowledge of the medium and frequently draw from a small and outdated pool of game titles. This has sometimes led to erroneous classifications of the types of narrative, erroneous readings of player's agency towards the story as well as unrealistic predictions on the storytelling future of games which did not take into account the role, state and limitations of the AI techniques implemented. For example, discrepancies exist between the medium’s current state and a promising storytelling future imagined by Murray (1997) and Ryan (2006). Using Star Trek’s Holodeck example, Murray speaks of future games as a narrative stage in which users participate and become emotionally involved in a story that grows and develops around their actions. They are able to interact with NPCs who are able to autonomously think and formulate independent responses based on the user’s input. Similarly, Ryan describes this as the ultimate interactive fiction, in which ‘the plot of a novel is generated live’ (116). Such a scenario would seem to require synthetic agents who are not only aware of their environment, but who can indeed elaborate thoughts and abstract thinking and formulate it through verbal and physical interactions with the user. While the non-deterministic implications of such developments would make the gameplay experience closer to real life, synthetic agents would need to develop human-like consciousness and cognitive capabilities and this is still beyond the reach of science, known as the hard problem of AI.

Therefore, promising as this future appears to be, its speculation emerges from wishful thinking rather than a realistic perception of what the medium can actually do in terms of narratives and player’s level of agency and involvement in the story content. Instead, this study has looked at the narrative architectures of a large number of current and less recent titles, paying attention to what game components designers use to facilitate and automatize the storytelling process. This has led to an in-depth analysis of how the story is delivered in the game environment and the consequent consideration of the AI as the only possible entry point to insert a non-deterministic system which may exert an influence on the narrative structures.

The investigation carried out in the research has also benefitted greatly from a thorough analysis performed on each sample from the body of game data available. It is only after having explored all types of interactions with all the reactive elements of the game world and having discovered all the story variations of a given game by completing the single player campaign multiple times that it becomes possible to gain a clear picture of a title’s narrative structure and the role of its AI architecture. Another feature that has greatly contributed to analytical constructive gameplay sessions is represented by competence and familiarity with interfaces, controls and gameplay mechanics of games belonging to all genres. Indeed, competence in this sense is an essential element for researchers willing to provide an in-depth and meaningful analysis of a title instead of merely scratching the surface.

The attention paid to the current state of game development, along with an in-depth analysis of the several types of systems in nature, have finally made it possible to identify a non-deterministic system applicable to game AI. This represents one further positive element of the research and its final contribution which takes the form of a model which can be applied to current game design and is compatible with the present day's hardware setups and computing resources. Furthermore, details are provided in order for the model to serve as a useful starting basis for designers interested in applying the nonlinearity of Cellular Automata to their games.

However, it is in the elaboration and presentation of the model that an inevitable weakness of this research can be found. More specifically, regardless of the details provided of how implement the program on both hardware and software environments, and the various examples discussed on how this would affect in-game narratives and gameplay experience, thorough testing and development are still needed to refine and optimize the program to suit the needs of future game design.

The hypothesis provided to the research question through the elaboration of the nondeterministic Cellular Automata model is the result of a theoretical approach. As such, it is in my hope that its validity be tested by designers and AI engineers willing to experiment and bring a qualitative revolution to the way stories and events in video games are experienced.

The medium of the video game currently represents the most promising platform for bringing a revolution in the way stories are experienced. While the conditions and required knowledge for fully conscious virtual characters are still beyond the reach of science, this study demonstrates the existence of an alternative path where to set the premises for a nondeterministic innovation of narrative. This path leads to the harnessing of the nonlinear dynamical properties of Cellular Automata in order to create pockets of complexity within current game AI architectures enabling synthetic agents and game world elements to display emergent and unpredictable behaviour. This experimental path can already be adopted with the tools currently at our disposal, and may soon lead to the creation of a game which tells a different story every time it is started; a story which rewrites itself in the absence of a pre-established authorial intent, and is a true consequential result of players' decisions.

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