MODELLING AND SIMULATION OF DOPAMINERGIC SYSTEM IN ADDICTION CONTEXT.
THE CASE OF INTERNET ADDICTION

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ABSTRACT

The aim of this work is to study the addiction and its manifestations in the current society and to understand its peculiar characteristics, in relation with the context where the addiction develops.

Addiction is a social phenomenon characterised by sociological and neurological aspects. From a behavioural point of view, it can be considered a sort of antidote and self-medication, which was adopted to counter a sense of discomfort and inadequacy; from a neurological point of view, it has been shown that the origin of an addiction involve different neurological factors and, in particular, the dopaminergic system.

The dopaminergic system has key role in the brain: it is involved in several fundamental mechanisms, as for example Parkinson’s disease and schizophrenia, but it is also associated with the addiction.

To improve theories of how this neurological structure works in an addiction context, they were used modelling and simulation from computer science and different sociological and psychological theories about the addiction problem.

Taking into account the mathematical models on dopaminergic system developed by Gutkin and Samson, I have developed a simplified mathematical model, to which has been added a “memory” mechanism, to represent the tolerance, essential phenomenon for the development of an addiction.

The basic model obtained was then described using the theory of Timed and Hybrid Automata, and has been used to study the reaction of the system to different types of pulse: constant in time, at increasing intensity and at a close frequency. In particular, two types of simulations were made, using Java code, focused on Internet addiction and technology, to analyse the relationship between user and technological object and between users in a computer-mediated communication.
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1 INTRODUCTION

1.1 Introduction and motivation

This thesis aims to improve theories of how the dopaminergic system works in an addiction context, by making use of modelling and simulation from computer science and different sociological and psychological theories about the addiction problem.

The main focus is characterised by the dopamine system, which plays a key role in the brain: it is involved in several fundamental mechanisms (such as for example motivation, decision-making and motor control) and is also associated with particular disorders, as for example schizophrenia, Parkinson’s disease, and principally, with the addiction. The dopamine, in fact, is a neurotransmitter that, as demonstrated also in many different laboratory experiments, is involved in the mechanism of reward system and connected with “the part of brain that establishes communication between past experience and future decision-making” [1].

To get a comprehensive perspective on the problem of addiction and the role played exactly by the dopaminergic system, the project combines two points of view: a sociological aspect, that was developed at the University of Durham (UK), during my permanence in England, with the help of Gerald Moore, Assistant Professor of Digital Studies; a computational aspect, developed at the University of Pisa, with the help of Paolo Milazzo, Assistant Professor at the Department of Computer Science.

The first part provides an overview of the main sociological theories on the problem of addiction, focusing on the causes and consequences of this phenomenon has on human behaviour, in particular, the inquiry will move to a new kind of addiction: the Internet and technology.

Technology, above all, has changed many aspects of people life and has influenced people’s behaviours, modifying, daily, their actions and spreading new needs, because of its capacity to simplify the achievement of many human tasks.

The French philosopher of technology, Bernard Stiegler, talks about “grammatisation” [2]: the millennial process that brings to the exteriorisation of
memory, through the birth and the development of material supports, like letters, words, writing, and code. Over the years, technical objects have been able to reinvent the nature of man: smartphones and similar are able to extend the communicative capacity of people and their senses and horizons are considerably increased.

In other words, that technological supports become artificial limb for people and for this reason, Stiegler and other researchers talk about “organological revolution”, that means a “reorganisation the human body and sensory cortex”. New instruments and techniques have implicated innovative methods to know adjacent reality and, especially, to practice a greater control of the environment.

For this reason, Stiegler introduces also the concept of pharmakon (taken a loan from The Phaedrus of Plato) hard to translate perfectly, because there is no direct English equivalent, that signifies that something is both “illness and cure” [3], and he uses this to describe the nature of technology, that is “cure” when we consider it as external memory supports, instead a “poison” when we consider it in the basis of addiction, because people can’t exist without these technical supports in which we are externalised [1].

Stiegler’s point of view is assisted by the recent neuroscience theories about human brain plasticity, that confirm how a prolonged and repetitive use of technology modify the brain structure and dopamine system. These brain changes are provoked by high-intensity stimuli that alter the natural function of dopaminergic system, that reveal oneself as craving, withdrawal and other addiction symptoms.

The second part focus on the addiction is focused on computational modelling of addiction. After an initial investigation of the qualitative data of the process that we want to analyse I created a computational model that faithfully represents the operation and interaction between all parties that dynamically compose the dopaminergic system. The use of mathematics, statistics, physics and computer science to study the mechanism and behaviour of complex systems. As explained by Ingalls: “each component of a mechanistic model represents some aspect of the
system being studied; modifications to model components thus mimic modifications to the real system” [4].

To use a mathematical model means to do an abstraction of reality, and so, to focus the attention on many aspects of the object of study: this allows to investigate on the mechanisms behind the biological process. From this realisation, we can have some advantages: we can consider the mathematical model as a “working hypothesis”, because using simulation model we can study the process in new way, that is difficult to reproduce in a lab; furthermore a simulation runs in few seconds and without real costs. Obviously, also the results of this study are hypotheses, but if the model respects the natural features of the object of study, negative results help to build a new correct model.

To describe the dopamine system, I resorted to the formal model of Hybrid Automata, that we can consider as a generalisation of Timed Automata, for a mixed discrete-continuous system, where the dynamic change of variables is modelled by differential equations.

In this way, system’s behaviour is algorithmically analysed and on this, starting from the theorised model of Boris S. Gutkin, about nicotine administering, and using also the sociological theories described in the first part, I realised my simplified model, and I realised two simulation, using Java programming, that considers different kinds of stimuli (stable or varying the intensity and the frequency of impulses) and contextual factors: one simulation explores the interaction between an user and a technology object; the other one explores, instead, the interaction between users, in a computer-mediated communication.

The aim of this work is to study the addiction and its manifestations in the current society and to understand its peculiar characteristics, in relation with the context where the addiction develops. In line with the objectives of Digital Humanities, I create a connection between two fields: of the one part there is human science (and so sociology, anthropology, psychology), that has the theoretical role in this work, and at the other part there is computer science (and so all the potentiality of Java programming), that represents the analysing tool.
At the conclusion of this project, in fact, particularly exciting was the possibility to use different theories, belonging to different research fields, able to complement each other. The key point of the research was primarily to consider, and insert during the simulation, even the contextual factors described in the first part, who had a minor role in the simulations of previous authors. In my opinion, considering the motivations, the social and individual needs aspects allows to analyse the functioning of the dopaminergic system on a larger scale and not limited only to a purely physiological description. Thanks to the interaction between computer science and sociological science, it was possible to understand better the role of dopaminergic system on human behaviour and, above all, the role of environmental factors on the addiction development.

1.2 Organisation of the thesis

The thesis is organised in two parts. As said before, the first part concerns the sociological issues about addiction and its spread in the society. Instead, the second part is based on the development of the addiction as computational process.

After a brief introduction that summarises the phases of this research project, the aim of the second chapter is to examine the general concept of addiction, trying to understand how addiction is born and develops; why people become addicts and if it is possible to correct an addicted behaviour. The main question of this chapter is, above all, to investigate the nature of an addiction: if it can be considered a disease or a wrong choice.

The third chapter is focused on the role of the brain in addiction behaviours. By means of neuroscience and its last theories, I analyse the role of the dopamine and the reward system, specifying their interaction with the context. Using some neuroscience concepts, I explain the consequences of addiction in the human brain, because of the reciprocal effect between neuroplasticity and repetitiveness.

The fourth chapter is based on the link between users and technology, in the Internet era, and the three main addiction forms: social network, gaming and surfing. The
aim, in this case, is to understand what pushes people to become addict and what changes in their behaviours when there is a particular inclination to fitful use of technological applications.

The fifth chapter focuses on the illustration of mathematical concepts that were used to develop this project, as for example: differential equation, Euler’s method, Timed and Hybrid automata theory. The sixth chapter is focused on the description of dopaminergic system as a dynamic system, that can be studied and represented by mathematical and computational model. In particular, they are illustrated the Gutkin’s and Samson’s models.

The seventh chapter is focused on my model on dopaminergic system in addiction context, that can be described using the theory of Hybrid Automata.

The eighth chapter, in the end, assembles all the simulations, realised in Java code, to study the effect of different kinds of impulses, for frequency and intensity, on the dopaminergic system. In particular, some simulations analyse the interaction between user and technology and between users in a computer-mediated communication.

In the end, in the last part, I analyse the conclusion, the results and the possible future applications of this work.
2 TO DEFINE ADDICTION

2.1 What is addiction?

Addiction is a social phenomenon that has had different interpretation over the years. In the past, for example, it was considered a sort of moral failing, a kind of insanity, a sin, a disease, a wrong choice [5]. From 1960s, instead, some researchers started to analyse this problem from different points of view, trying to understand its various aspects: psychological, genetical, biological and so on.

Amanda Roberts and George Koob [6] define addiction as follow: “Addiction can be defined from a behavioural viewpoint as repeated self-administration of alcohol or other drugs (AOD) despite knowledge of adverse medical and social consequences and attempts to abstain from AOD use. Typically, an addicted person’s daily activities are centered on obtaining and consuming the drug at the expense of social and occupational commitments”. They, in this case, only refer to substance abuse, in reality there are many types of dependence and symptoms, that may or may not occur, are the same. Many factors contribute to the development of addiction. A person’s initial decision to start to use a substance is influenced by genetic, psychosocial, and environmental factors.

The first step, to understand what it really is, is to discern from physical addiction with the nature of addiction [6]: physical addiction is a natural response of our body to some substances (like, for example, drugs or alcohol) that have effect on organism; the nature of addiction is a compulsive need, difficult to explain and to remove, that pushes the addict to act compulsively.

The addiction can be considered a kind of antidote to perception of empty and uselessness. According to Anderson, author of the book *Globalization of addiction*, we can consider addiction a rational response to our maladaptation to cultural environments [7].
We can describe it as an emotional relationship with an object or an event, that Damian Thompson, columnist of Saturday Telegraph, in his book The Fix [8], calls a “relationship of convenience”, because addicts start to look to these objects and events like the solution for emotional stability, frustration, disillusion and personal insecurity. Usually, addicted people choose something that they think they can control and manipulate. Effectively, addiction is also useful to substitute real affection with things, because things have not wants or needs like individuals, furthermore for addicts human relations have nothing guarantees and they are another source of tension and pain [8].

This assertion, however, does not take account of all the forms of dependence, which have for their object the social relations, like for example love, friendship or sex, that can be object of addiction. These social relationships, in fact, can be taken it to the extreme and become severely insane. This is demonstrated in the advent and immoderate use of pornography and social networks.

As you will be seen later is one of the reasons for which, in fact, in the contemporary society, social networks are very popular, in addition to allowing to establish a mediate and safe relation (by screen) between users.

The condition of dependency can be described by what is called the “Stop and Go” theory: “go” represents the primitive and animal part of our brain, that pushes up to obtain as much as possible; on the other hand, “stop” represents the rational and more developed part of our brain, which is important to hold out against all impulses derived from the surrounding space. In addicted people, the “stop” impulse is unheeded, and so they aren’t able to stop themselves. This is the reason why people eat, play at gambling machines or are connected to mobile phones for hours. They find something that help them to be totally disconnected from reality: a way not to think of their own problems. Thompson argues this concept asserting that addiction is not only an escape from their monotonous life, but it is the progressive replacement of people by material things.
Addiction produces only temporary sensation, that creates false illusions: the pain can be defeated, but only momentarily, in fact, it returns deeper and more persistent. For this reason, it becomes a vicious circle: addict is totally seduced by the feeling of ostensible calm, so he or she starts this process, in which the only consequence is the loss of control. “When compulsive eaters feel sad, they eat to feel better; when alcoholics start to feel out of control with anger, they have a couple of drinks to get back in control”.

Dependence is a defence system, that, actually, follows a logical progression. Its seductive part is exactly this: a false and illusion control, caused by a positive and pleasurable mood change. This defence system pushes addicts to live simultaneously in two different worlds: reality and in a “trance” condition, the way to create a virtual situation of harmony. We can consider the trance like the solution for the suffering: it is a condition of alienation, an indispensable state to distance yourself from life problems. Trance starts, above all, during a monotony circumstance, like for example when the addiction state is accompanied by a recurring action: to do always the same gesture, in fact, helps to clear mind from thoughts. For all these reasons, dependence is an escape from reality: to create an own world and existence is the cure to be happy and content, a method not to feel yourself judged from the others. Usually, there are three phases [9]:

- **Engagement**: when an user starts to learn how to use something to feel better. In the first moment, there is a sort of knowing, which can define “preliminary”.

- **Substitution**: from preliminary knowing, you become totally addicted to it, because it becomes the answer to pain.

- **Escape**: you feel calm, peaceful and happy only during the uses of this addicted thing. It is an escape, because it is clearly an attempt to go away from the reality.

These three phases are very common, above all, for the technological addiction, because they are able to show the adaptation describes by Stiegler, as we will see.
In fact, the first phase, engagement, represents how people learn to use a new something of new (like an app, a software, a new technology or similar).

Addict’s lifestyle turns into obtain instantaneous gratification in material things, with a lot of consequences for his life. All objects, in fact, have a normal and socially acceptable function, but addiction modifies this role because of the insane relationship that is established between person and objects. This abnormal relationship makes people’s life very lonely and isolated, because, as disclosed earlier, they removed all their affections, both consciously and not. When they are in the described mood of trance, it changes totally their consideration of reality: they lost the common sense of things, like for example space and time. Executing over and over again the same gesture (playing at gambling machine, updating social networks homepage or eating/drinking compulsively), they forget surrounding context: a lot of times, they forget to drink water or to eat something, while they are playing, or their children; or once again they ignore, in that moment, money value.

2.2 Escape and self medication: who is the addict?

Everybody can be subject to addiction, but it is very difficult to understand what are the reasons to develop addicted behaviours. Addiction is a complex phenomenon that appears to be multifactorial in origin, stemming from pharmacological, biological, psychological, and social factors [9]. At the bottom of these problems, there are a lot of traumatic events.

According to Kimberly S. Young, author of the book *Caught in the Net*, the main troubles are: loneliness, marital discontent, work related stress, boredom, depression, financial problems, insecurity about physical appearance, anxiety, struggles with recovery from other addictions, limited social life.

All of which are very common, especially, in our society and it is the reason why addiction is very popular among people: it is the escape from their unhappy lives.
According to United Nations Office on Drugs and Crime (UNODC) in the 2012, 230 million people around the world - 1 in 20 of us - took illicit drugs. According to World Health Organization (WHO), the United Nations Office on Drugs and Crime (UNODC), and the Alberta Gambling Research Institute:

- 5% of the world's adult population (240 million people; 8% of men, 1.5% of women) have alcohol use disorder;
- 22.5% of adults (1 billion people; 32% of men, 7% of women) smoke tobacco;
- 1.5% of adults have problem gambling (even if, the researchers were unable to find global estimates of this kind of addiction).

Estimates regarding addiction for the technology and Internet are not very accurate, at the time. The main problem, in this case, is that it was not yet reached a unanimous vision towards this problem. Not all perceive the immoderate use of social networks, the urgent need to be connected as a real addiction, and recent studies, such as those conducted by the University of Hong Kong [10] (where the problem is already perceived as real) are by far reversing the trend.

More than once, to be addicted is an unaware attitude: at the beginning it is not something worrying, but with time, it is, increasingly, something you can count on. So, it grows a problem, not only for addict, but for his family too.

### 2.2.1 Environmental factors

Many studies reveal that this process is highly influenced by the context and environmental factors. Among them certainly much they influence the sex, age, social background and the sociological profile of the subject in question.

Individuals choose addicted “substance” based on three factors:
- **Education and family background**: the own personal path contributes to accept or deny some attitudes. In general, you can be conditioned by own parents and their addictions;

- **Availability**: addict tends to choose something simple to find;

- **Economic resources**: money have a great bearing on addicts, more they have money, more they use them to foment their addictions.

The second point, in particular the availability, was very important in the past, when addiction is considered a sort of sin, more than a wrong choice. A lot of examples can show how the willingness could be decided to spread a peculiar substance: in the 18th century, there was a Gin epidemic among English people, because this alcoholic drink was very usable; soldiers, during Vietnam war, are addicted to heroin because it was very cheap and common; at the end of the 20th century, there was an incredible diffusion of gambling machines and casino, that, in certain cases, continues again but on the Web.

To reinforce this manner there is the inclination of people to emulate each other, which proves beyond that social factors are prevalent and confirming that addictions change though years. Edwards, in 1976, noted that what constituted an addiction problem varied according to the social setting; what was seen as problem by one person might been seen as normal in a different or class setting. In addition, Kelley, in the 1967, observed the piece of social behaviour depends on the interaction of three factors [11]:

- **Consensus**: what thought people about an attitude.

- **Consistency**: how many times people had this attitude.

- **Distinctiveness**: how much is diffused this attitude.

Inevitably, so it shows that is the people’s look to structure the addictions, that are changed might following a trend.
Graham noticed that “the world is more addictive than it was 40 years ago” [8]. One of the reasons is the arrival of Capitalism and the consequential spread of Globalisation, that is allowed the sharing of the same substance in different parts of world. Also technology has an important role in that sense: technical structures have had the assignment to develop the idea of velocity and simplicity, that can be behind the appropriation and adaptation to the addictions. Social networks, pornography, compulsively nutrition or gambling are totally amplified by technology. And the acceleration mood has made all more uncontrollable. This is also the reason that entailed to the development and change of the addiction, compared to the past.

You can define addiction like “something without which you can't live”, because you become totally submissive to it, so, in theory, whatever can become an addiction object. However, there are particular inclinations, influenced by the context, that pushes people to have sometimes the same dependences.

No doubt, alcohol and drugs aren’t born in the modern society, but they are an heritage of the previous years. The first one was very popular in XX century and, in fact, it was at the centre of Prohibition: US government tried in vain to stop alcoholism overflow; the second one, instead, is considered the dependence par excellence and, even if its abuse is decreased in the last period, because young people prefer marijuana, there are once again a lot of people that choose them trying to escape from their problems or only for boredom.

On the contrary, in our society, as already mentioned, the new addictions are the result of the interaction between people and scientific progress, verifying one more time the relevance of the context. We can not deny that these new behaviours are the natural consequence of a capitalistic and consumer society, where it triumphs the desire of fast rewards, without waiting time and where the feedbacks are immediate. Addiction for gaming, virtual reality, social networks and so on are not always recognised like dependences, because public opinion think that stay at the laptop for hours and to use a screen to relate yourself with the world are a normal attitude. In our society, the force of Internet and its applications is exactly to mediate reality and to know from the world through images on a desktop, feeling safe.
Rat park experiment [12]: in confirmation of what environmental factors are fundamental for the development and for the determination of dependencies, there is the famous experiment of the rat park, designed by Bruce Anderson, Professor Emeritus of Simon Fraser University.

To study drug addiction, in the early ’60s, in fact, had used the Skinner box, to better understand the drug's effects on mice.

The rodents were placed inside boxes, without contact with the outside, and could independently manage the amount of drug administered, simply by pressing a lever.

The experiment results showed that the mice were vulnerable to drugs: they became addicted and the amount of injected drugs increased dramatically.

They were not, however, been considered three key elements for the success of the experiment:

- The mice in their natural environment are highly social creatures, which tend to establish a lasting relationship with their partner and to also have a large family.
- You can not really compare the drug abuse of mice with that of humans, because mice are found in a completely alien environment to their natural environment, while people with no addiction.
- The behaviour and motivations that drive an animal to abuse chemical substances that are not naturally the same as those of the people.

The main problem caught by Professor Anderson was that the mice were in a difficult situation, and isolation and, therefore, you could not judge their behaviour. Anderson decided to build a park rat, where rats could recreate their natural environment, playing and procreating. The amount of drug used was decreased significantly. This showed that a different context, purposeful and sociable, alters behaviour towards dependency. Anderson also extended his judgment also to what had happened in the early American colonies, when the natives, by comparison with the style and habits of Western populations, in a difficult situation, they found relief by using different types of substances.
He writes: “In both cases there is little drug consumption in the natural environment and a lot when the people or animals are placed in an environment that produces social and cultural isolation. In the case of rats, social and cultural isolation is produced by confining the rats in individual cages. In the case of native people, the social and cultural isolation is produced by destroying the foundations of their cultural life”.

### 2.2.2 Genetic factors

Disorders related to addiction are increased in the last years and this has prompted researchers to also question the biological reasons of this problem.

An important element that they have started to consider, around 1960, is certainly the genetic factor and its relationship with environmental features. It is essential to underline that try to find a genetic vulnerability in subjects, doesn’t mean that there is an “addiction gene”. Instead, it is the attempt to study “the complex interactions between an individuals’ genetic markup, or genotype, with their unique environment and history, that determines their eventual patterns of behaviour” [13].

Since only some individuals develop an addiction, it is clear to ask what are the distinguishing factors.

Fundamentally, there are two kinds of human studies: twin and adoption studies. The first one is very useful, because monozygotic twins share the 100% of their genes, so it is possible to study how genes and environmental factors influence the human behaviour about addiction.

The second one method, instead, tries to understand how much the behaviour depends from adoptive parents or biological parents, and analysing their addiction history, if environmental properties are more important than genetic ones.

Up until now, these studies were carried out in particular on three types of dependence: drugs, alcohol and smoking, and results seem to confirm increased vulnerability to external factors, more than genetic ones. In fact, in a study of 1600
Dutch adolescent twin pairs we found that 59% of the inter-individual variation in smoking behaviour could be attributed to shared environmental influences and 31% to genetic factors. The magnitude of the genetic and environmental effects did not differ between boys and girls [14].

2.3 Addiction: a disease or a wrong choice?

One of the main discussions on the theme of addiction is if to consider this phenomenon a disease or a wrong human choice. At the bottom of this long and difficult debate, there are two school of thought: one, more medical, that underlines the many aspects (like craving and withdrawal) that makes addiction more similar to a disease; one, more anthropological, that, instead, considers this event only a mistaken behaviour.

2.3.1 Addiction as human disease

The psychiatrist Nora Volkow, as well as top of the addiction, she said that it depended on both the brain that the behaviour. But, for a lot of people, above all for physicians and for addict’s family, the addiction the dependence is to be considered only a disease, and the reasons are substantially two:

- **Brain’s changes**;

- **Control issue**;

In the first case, physicians prefer to refer at the addiction as disease, because in this way it is simpler to find cures and therapies. It was very developed also by narcotic and alcoholics anonymous, because it was highly functional: addicts are considered like patients, so they have to follow some medical indication, to return in good health
and the curing is the aim to reach. And if addiction is a disease, the addicts deserve compassionate care, help and treatments. A reason for this is incontrovertible confirmation that, indeed, in addiction there is a change at the neural level, we studied mostly from neuroscience that seeks to have an interdisciplinary approach on the understanding of the birth and development of addictions. The brain change is, in fact, considered like a brain disease, without considering that the brain change is part of its evolving nature, just call neuro-plasticity, particularly sensitive to the emotions produced from the experience, especially if frequent, as will be described in the second chapter.

In the second case, for affects and family of addicted people is simpler to accept the addiction as disease, justifying the problem as something that you can not control. It is more respectable than labelling it like a moral problem or a mental disorder [15]. You can not defeat easily an illness, but you can do everything to make this happens. And in addition, there are two other reasons, that could support this theory: we can note the same kind of brain’s changes, both in addiction and in disease, as written previously; there are genetic studies that reveal heritable traits that predispose people to addiction.

Another decisive factor is the consequence of addiction, the physical dependence, and so the feeling to be totally unable to live without addiction, even if many researches show that this human condition is not sufficient to become addicted. Because, for example, sometimes patients, undergo to medical operation, swallow analgesic narcotics to avoid pain; for some of them, these medicines cause withdrawal symptoms, but it is only their choice to continue the dosage. In this sense, also the “loss of control” would seem a confirm to this concept. But, both this and “denial” (the first phase after overdose) confirm only chronic and progressive progress behind dependence. It is a typical effect of some specific substances, particularly strong, like drugs and alcohol.
2.3.2 Addiction as wrong choice

For sociologists and anthropologists, addiction is not only a disease, it is a choice, provoked by the repetition of the same thoughts and behaviours until they become habitual. It is important for this theory, above all, to discern between disease symptoms (like craving and withdrawal, that could be considered disease expression) and the reasons (usually mental disorders, apprehension and other kinds of pain) that result in dependence. It is a sort of loop: an individual learns that there is something, able to alleviate instantly and without stress every type of sufferings, and so he or she resorts to it every time.

Obviously, addiction produces some brain and body changes, that are similar to a disease, but they are just consequences of wrong and insane behaviour, like drugs and alcohol.

According to Marc Lewis [16] there are many reasons to affirm that the addiction is not a disease:

- The measurable brain changes that characterise addiction usually disappear when people stop using;
- The loss of synaptic density in certain prefrontal regions is often considered the golden proof that addiction is a disease. But, instead, it is synaptic pruning, that represents the normal cortical development and it is the result of learning;
- The role of genetic factors is still emphasised by physicians, to the detriment of the predominant role played by environmental factors;
- Disease are based on exposure, not experience as is for the addiction;
- The powerful attraction to addictive substances is a response to some form of suffering, as for example negative feelings and isolation. This was also demonstrated by the experiment Rat park;
- Some medications can be used to relieve withdrawal symptoms and reduce addictive urges;
- The consequences that occur at the level of the dopamine system, not only depend on dependence, but can also be caused by particular medical drugs;

- Certain social situations, such as love, friendship and so on, improve much the state of dependence. That does not apply only if it were regarded as a disease.

According to Marc Lewis, in fact, more than considering addiction a disease, you have to look to it as a process that involves an accelerated learning, based on the fact that the attraction (considered as the union of desire and attention) produces immediate feedback, which in turn produces the changes to the level of the synapses, which transform the attraction itself in a habitual behaviour, which therefore is executed repeatedly. We can consider the addiction like “a self-reinforcing habit based on intense emotion, a motivated repetition that gives rise to deep learning” [16].

According to neuroscientist Kent Berridge [17], the desire has the critical role in the addiction, because addiction is about wanting, not linking.

A particular metaphor, used in the work *Introduction to addictive behaviours*, is useful to explain this point of view: during the late 19th and early 20th centuries, missionaries went to Africa, because of their desire to help people, but many of them caught malaria and died. The disease was malaria, not the decision to undertake the travel, that was only the motivation.

For a behaviourist perspective the initiation of substance use is related to three factors:

- **Availability**: as written beforehand, the context plays an important role in addiction. A person is more tempted by something that can reach easily or by something that a lot of people just had used.

- **Lack of reinforcement for alternative behaviour**: it occurs when some common behaviours and socially approved, such as work or study, are not quite gratifying. Therefore, they tend to choose behaviours, also not socially permissible, but that offer an instant gratification.
- Lack of punishment for experimenting: (maybe, the most important) occurs when the choice of wrong behaviour is not balanced by an immediate punishment, as instead it happens for socially accepted behaviours. When not studying, the result is inevitably a bad grade; when taking an addictive attitude, the consequence can occur even after a long time. This causes people to stop after being addicted, because initially they do not feel motivated enough to quit. Indeed, they are pervaded by a feeling of euphoria and sharing.

These three factors together represent a sort of “initiation” in the social environment, a type of activity that gets involved especially who is not able to find happiness in everyday life, because he finds the world boring and meaningless and without stimulating. Also, initiation is encouraged by three different types of reinforcers: euphoria, social variables, elimination of withdrawal sickness.

Instead, there would be four reasons to start to use an addiction substance:

- Facilitation of social interaction.
- “Time out”: repetition is a help to delete panic and to take a break from social life.
- Solidarity in a group: to use the same addiction substance (or not) it is important to feel member of an ethnic group.
- Repudiation of middle class or “establishment” values: it is a way to break with communal thoughts.

External contingencies, in the radical behaviourist camp, are decisive for the determination of human behaviour, but according to Albert Madura, leader of cognitive psychology, a great part is playing by self regulation.

According to him, in fact, the behaviour is the result of three terms and their interaction: cognitive field, behavioural field and environmental determinants, but each one choses own limits to act. Self regulation, concept of Social Learning Theory, proves that: people and their environments are reciprocal determinants of
each other; external factors are able to influence the acquisition and regulation of
behaviour; when people are addicted, they are able to regulate their own actions via
internal standards and self evaluative assessments. They create their own standards to
insert the addiction in their habitual world. In the scheme of the Figure 1, it is possible to note
the kind of interaction that is established between factors: every vertex, in the triangle, is affected
by the other two.

In the Social Learning Theory, the self regulation is also determined by two type of
expectations: outcome expectations (that is a person’s result that a particular event
will happen) and efficacy expectations (that is a person’s belief to obtain the result,
based on performance accomplishments, vicarious experiences, verbal persuasion,
emotional arousal). In particular, efficacy expectation are important in relapse
prevention. Relapse is very communal between addicts: it is an “unrestrained” return
to the addiction, caused by stress or lack of motivation. One of the reason is the
subordination of the individual to society, that generates two problems: one is the
elimination of the conditions that creates tension, the other is the problem of finding
a mode for relief tension. It is a loop, which without the right kind of motivation and
decision, can have negative consequences for individuals.

That it difficult to understand is: how is addiction a choice, if people know all
negative effects of this? So, why, for example, do people continue to use drugs, like
heroin or cocaine? To answer, many sociologists talk about a third school of thought:
the self medication model [16], that derives partly from psychology, partly from
sociology and medicine. According to them, all of these behaviours are dictated by
the will to go beyond to some adolescent traumas, as a sort of natural consequence
after a post traumatic disorder, resorting to wrong methods. In this sense, choice it is
totally correlated to environmental factors.
2.4 Is it possible to remove an addiction?

Not always, addicts are aware of their addiction. The addiction, in these cases, is seen as a sort of solution, an escape from reality, so they don’t realise that this compulsive behaviour makes worse hugely their feelings of frustration and stress and the awareness arrives very late.

In the past, many approaches, above all from medical point of view, have been tried to solve the problem, but therapies and cares, that contemplate the addiction only as a disease, failed miserably. In the early 1900s, a lot of hospitals promoted their different methods as, for example, “prefrontal lobotomy” or strange and miraculous medication, like which of Dr. Leslie Keeley, that spread a lot of rehab clinics, completely shut down by the end of World War I [5].

2.4.1 The Alcoholics Anonymous

One of the most famous approaches became surely the Twelve-Steps program, a set of twelve rules to follow to cure many kinds of compulsions, that is communal again today. This guideline is proposed originally by the Alcoholics Anonymous (AA), founded in 1935 by Bill Wilson for the treatment of compulsive alcoholism. Wilson wrote the rules in 1944, all included in the book *Twelve Steps and Twelve Traditions*, published in the April of 1953.

For him and the other supporters, addiction has to be considered as mental and spiritual “malady”, that can be defeated only following, pedantically, all the twelve principles, at the base of which there is a religious influence and not scientific: for the AA members, in fact, only the God’s help is decisive to stop to be an alcoholic, as written in the step number seven. Basically, the rules represent a path to reach the healing: not drinking more, have a sponsor, share own feelings about alcohol, partecipate to the AA meetings and divulge its benefits. The last one is very important because of this plan of action, AA has received a lot of consideration in the political and national health programs: AA has been extraordinary effective at
influencing public opinion and policy toward a favourable view of its idea, and so to see the alcoholism, in particular, and all the other addictions, in general, as a chronic brain disease.

One reason for the success of the AA is definitely the social support that seems to give its members, which would be admirable if we do not consider the fact that this same philosophy is shared by other types of listening groups. Nevertheless, the AA is however still considered - wrongly - a real treat. But this group appears to be surrounded by an authentic myth that, over the years, has incited some misconceptions. For example, members support the idea that we can really start a healing path, only after reaching the peak of own addiction; that an addict may be heard and aided only by people who have had the same problem (hence the need to have a sponsor); that alcoholics, specifically, but all addicts, in general, can be treated equally, regardless of the specifics of individual cases and that, again, all those who are suffering from addiction are definitely character disorders.

This allowed the spread not only of many centers for Alcoholics Anonymous, but also expensive rehabs, that exploit public opinion to foment a real business, without concrete and demonstrated results of success.

Many scientists, in fact, making use of the help of many researches, have tried to analyse the data concerning the percentage of remission between alcoholics: the data obtained are usually incomplete and distorted and, in total, only from the 5% and 10% of all members are really sober after a period in AA. Even if, the AA uses different academic articles to supporter the 12-step movement, no experimental studies unequivocally demonstrated its effectiveness, as for example the study of Rudolph and Bernice Moos of Stanford University, in the 2005, that became one of the most cited data in support of Alcoholics Anonymous, although as noted by other researchers, including the same Lance Dones, there are many questions about the validity of the data and the analysed samples, which do not represent all of the AA members. In one critical omission, the conclusion of the Moos study ignores all the people who died, as if they had never existed at all, and even if their category statistically consumes the most alcohol [5].
But, given that one of the principles is also proselytising, despite the very low success rates, continues to spread the idea that this method works, even if many patients and members who have witnessed, especially on social network and websites, its total inefficacy, above all because of religious course of action. Furthermore, it is common practice to blame not the failure of the method, but the inability of the member to give up own previous life, linked to addiction, and only embrace 12 steps principles.

Another point against dell'Alcoholics Anonymous, is certainly the importance it attaches to the spirituality: this, according to interviews with its former members, is not always an advantage, but to entrust such a such importance to the religious aspect, causes they dash any form and level of dependency with the same mechanisms and without distinction of any kind.

The main problem when trying to solve the addiction is to understand what motivates a person to cyclically perform the same actions. Usually, it is well rooted motivations, hidden in intimacy and difficult to resolve. Instead, attending AA, with difficulty, people are successful to build a different context for their life outside the listening group, lacking a positive reinforcement.

So when no change occurs, frequently, person never stops to be addicted, but he or she finds a new obsession, able to substitute the previous. On this scheme, designers or other “business roles” work to find other kind and level of dependence. In fact, as described, in Addiction by design [18], work of Natasha Dow Schüll about the problem of gambling machine in Las Vegas, connect their knowledges about social environment, people’s physical and mental needs, to assemble the perfect casino, where users can stay there for a lot of hours. They study all the factors that could be interact with players: aroma, sounds, lights, temperature. Each elements, that together, modify sensory atmospherics and allow to players to sit and play, without lack of concentration and in total absorption, like in a sort of rat trap. People require always new incentives and for this reason study always more kind of addictions: for example, for gaming, they develop other functions, actions, levels, characters or skills to reach; for gambling, they study new type of machines, with different manners to bet. This is in line with the reward system that govern our brain.
Even if, methods like 12 steps or the rehab try to promote the view that the addiction is a chronic brain disease, research evidences that it is not true. So, to have a supporter group and to some activities are important steps to achieve emotional stability, and it is one of the reasons that push people to attempt this way, however data demonstrate that the greater results are connected to spontaneous remission [19], that is when people quit addictions on their own without rehab or AA.

2.4.2 The spontaneous remission

The term spontaneous remission, according to the vision of neuroscientists, is really controversial because this process is a difficult decision for the addicts, that requests a lot of work and maturity. According to the last survey studies of the National Epidemiological Survey on Alcohol and Related Conditions (NESARC), the effect of spontaneous remission is inversely proportional to the age: in adult and old age, there would be a greater tendency to quit an addiction, as shown in the Figure 2.

The reasons have to be researched in the environment and in the neurochemical changes, which take place in the brain. During adolescence, people tend to take riskier actions for themselves and for their own health, also relying on the spirit of the group emulation. At this stage, it is important, above all, the role played by the
oxytocin hormone (also called "empathy hormone") that encourage to the imitation of own peers. In this sense, the teenagers would be much more inclined to take dependency attitudes. On the contrary, in old age, there would be a counterview linked to changes in the environment, which would lead to having more attention on other factors, such as children, work, personal satisfaction.

So, how research shows people become progressively more risk averse with age. Dr. Julia Deakin [20] and her research team had 177 subjects aged between 17 and 73 take part in a computer based gambling task and found that risk taking behaviours decreased in proportion to the age of the subject.

Concerning neurochemical changes, instead, there are two important studies that have shown how the interaction between different brain components change the attitude to addiction. Dr. Laurence Steinberg [21] and colleagues studied 935 subjects between the ages of 10 and 30 and found that scores on sensation-seeking, risk preference, and reward sensitivity peaked between the ages of 13 and 16 and began to fall off thereafter. Dr. Steinberg posits that there is a neurobiological basis for this peer-mediated increase in risky behavior which is due to an increase in oxytocin receptors in adolescence. Dr. Tatia Lee and colleagues performed an experiment to measure the activation of the right insula1 of a group of younger subjects (12 subjects, average age 30) compared to a group of older subjects (9 subjects, average age 65) during a risk taking task: “The results were that the older subjects showed significantly greater activation of the right insula when making the risky choice than did the younger subjects, which neurobiologically identified the older subjects as far more risk averse and harm avoidant than the younger subjects” [22].

Physicians, as regards the total abstinence, as a method for recovery from addiction, have opposing opinions. Again, we must consider the context: the results depend mainly on the individual's subjectivity.

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1 The insular cortex is a portion of cerebral cortex. The insulae are believed to be involved in consciousness and play a role in diverse functions usually linked to emotion or the regulation of the body's homeostasis. These functions include perception, motor control, self-awareness, cognitive functioning, and interpersonal experience. See: https://en.wikipedia.org/wiki/Insular_cortex
3 THE ROLE OF BRAIN

3.1 How the brain works

In addition to medical and sociological reasons at the base of addiction, there is also biological and chemical implications. As we have seen in the first chapter, there are many theories and studies on addiction, but there is a topic able to connect different neuroscientists and physicians: the central role of the brain.

Many studies are beginning to find out what is the role of specific brain regions and how the neurochemical mechanisms involved and interact each other, modifying the reactions of the person and his propensity to addiction. These changes are not only visible in the behaviour, but also in the brain.

3.1.1 Neurobiology of addiction: an overview

Addiction is a phenomenon that involves the participation of various neural circuits, where for neural circuit means “a group of connected neurons that pass information related to a specific function” [6]. The dopamine system, the GABA system, the serotonin system and the opioid system are involved and have a crucial role in this process, instead the brain areas involved are, above all, ventral tegmental area, nucleus accumbens, prefrontal cortex and the amygdalae, as shown in Figure 3.

Concisely:
- The *ventral segmental area* (VTA) is a group of neurons located close to the midline on the floor of the midbrain, it is the origin of the dopaminergic cell bodies.

- The *nucleus accumbens* (NAc) is a region in the basal forebrain rostral to the preoptic area of the hypothalamus, it is divided in two regions, called core and shell.

- The *prefrontal cortex* (PFC) is the cerebral cortex which covers the front part of the frontal lobe. This brain region has been implicated in planning complex cognitive behavior, personality expression, decision making, and moderating social behavior.

- The *amygdalae* are two groups of nuclei, part of the limbic system and involved in many processes, as memory, decision-making, and emotional reactions.

### 3.1.2 The Dopamine System

Dopamine (contracted from 3,4-dihydroxyphenethylamine) is a hormone and a neurotransmitter and it plays several roles in the body and in the brain. In the brain, its function is as neurotransmitter and so it works to transmit signals from nerve cells to other nerve cells.

![Dopamine molecular formula](image)

The passage of information between nerve cells, produces a cascade of intracellular events that alters neuronal circuit activity. In the Dopamine System neurons are called dopaminergic neurons and are approximately 400000 (less than 1% of the total neuronal population of the brain). They were studied during a research, conducted in 1965, by Annika Dahlström and Kjell Fuxe [23], in which it was used for the first time the fluorescence histochemical method for the visualisation of these neurons.
cells, containing dopamine, and their pathways in the brain. The two main receptors of dopamine are D1 and D2: the first one activation is in general excitatory; for the second one is in general inhibitory. In this sense, D1 represents the “go” neurons, instead, D2 represents the “stop” neurons.

Only at the beginning of the XX century, namely around 1910 dopamine it was synthesised for the first time. In the 50s, however, they begin the realisation further studies on this. In particular, physicians discovered a significant correlation between the levels of dopamine and two neurological diseases: Parkinson’s disease (a degenerative state of the brain, because of the loss of dopamine in the midbrain) and schizophrenia (a mental disorder, characterised by the difficult to understand the reality and a huge level of dopamine). It is also involved in attention deficit hyperactivity disorder.

The functions of dopamine can be divided in two groups:

- **High level functions** include motor control, motivation, arousal, cognition and reward system;

- **Low level functions** include lactation, sexual gratification (orgasm) and nausea.

The most important syndrome, correlated to the low level, is the Dopamine Deficient Depression (DDD), that can cause chronic boredom, lack of personal satisfactory feeling, fatigue, decrease in physical energy. This shows how the neurotransmitter is associated with pleasure and elation and it is able to modify the human behaviour.

The aid of Positron Emission Tomography (PET) showed also the role of the neurotransmitter associated with dependence and addiction. In this sense, the psychiatrist Dr. Nora Volkow has made the greatest contribution: she has published

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2 Positron emission tomography (PET) is a nuclear medicine, functional imaging technique that is used to observe metabolic processes in the body. The system detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide (tracer), which is introduced into the body on a biologically active molecule. See: https://en.wikipedia.org/wiki/Positron_emission_tomography.
the strongest evidence of the involvement of dopamine in an addiction context. Volkow, using the PET, that was early used to study the brain in people with schizophrenia, started to study the brain of drug addicts and she suggested that dopamine and addiction establish “a vicious circle of physical brain changes” [24].

In her research, Volkow underlines that, using the PET, it was possible to note an elevated level of dopamine in the dorsal striatum, when the subject is vulnerable to stimuli related to addiction. In the first time, in fact, dopamine level increases, but after a prolonged use, its level decreases clearly: the rate of dopamine doesn’t reach anymore the initial level, before the addiction. This was discovered just by comparing different individuals: using PET, it was noted that addicted subjects were producing less dopamine compared to non addicted subjects, but they were much more sensitive to external stimuli. In other words, the abuse of a substance produces a disruption: the effects of repeated exposure alters the functioning of neural circuity and provokes complex behaviour (eventually tolerance, craving, sensitisation, dependence).

As written in Volkow’s paper: “Because the dorsal striatum is implicated in habit learning, this association likely reflects the strengthening of habits as chronicity of addiction progresses. This suggests that a basic neurobiologic disruption in addiction might be a DA-triggered (Dopamine system) conditioned response that results in habits leading to compulsive drug consumption”.

So, we can say that the chronicity which undoubtedly characterises addiction is inevitably linked to brain dysfunction, caused by repetitive compulsion, arising from environmental factors: the decrease of functioning of dopamine system reinforces the desire to be addicted.

3.1.2 The Serotonin system

Serotonin (5-hydroxytryptamine (5-HT) is a monoamine neurotransmitter.
If dopamine is the neurotransmitter linked to reward system, serotonin is linked to feelings of well-being, happiness, appetite, sexual behaviour, and emotional states. Studies reveals that the increase or decrease of serotonin level in the brain, is able to reinforce the consumption of alcohol and drugs, particularly [25]. This neurotransmitter is involved in the addiction behaviour and, how it was shown in many laboratory tests, is implicated in the “impulsive choice”, defined as a preference for smaller immediate over larger delayed rewards: the high level of impulsivity is considered a risk factor for addiction disorder, because of its capacity to amplify the circle at the bottom of dependence. And as revealed by some studies on gambling [26], this has been most remarkable among the gamblers, in who it has been demonstrated, several times, the inability to resist impulsive decisions. People with clinically relevant levels of impaired impulse control, including those with pathological gambling, or impulsive aggression, have demonstrated low levels of the serotonin.

This topic is strictly connected to Stop and Go theory, seen previously.

3.1.3 The GABA and the opioid systems

The GABA is the chief inhibitory neurotransmitter in the central nervous system and so it can be seen like a sort of brake to the compulsive need. It reflects the capacity of brain to repulse the “Go” impulse. Some treatments, for alcohol addiction, try to stimulate pharmacologically this neurotransmitter to calm down the drinking urge.

Instead, the opioid system consists of three receptors, mu, delta, and kappa and its function is to control pain, reward and addictive behaviours. The opioid system in a key position to modulate the circuit called positive reinforcement: that is when people learn from their actions, considering the emotional effect. We talk of positive reinforcement when the effects are associated to well being feelings and personal satisfaction.
3.2 The consequences of addiction in human brain

At the cerebral level dependence causes many changes, which are obvious both through tools, such as PET, either through changes in behaviour, mood and in the individual's physicality.

The short-term consequences, if we want to define them, especially concern passengers aspects, such as the change in mood. In the long term, however, the addiction has more severe consequences: these include abstinence, withdrawal, tolerance, compulsivity and impulsivity.

3.2.1 Craving

Two of the most important consequences of alteration of brain system caused by addiction are surely: craving and withdrawal.

Craving can be described like a compulsive desire, it is not a simple want: for addict people it becomes a need that they have to satisfy necessarily. This intense desire comes from having succumbed to dependence. “In fact, whether people resist the experience depends on whether they have good reasons, or not good reasons, for doing so” [26]. Craving is defined like a sort of anticipation of a positive effect, due to an addiction substance, for example drugs or alcohol. Sometimes, it is considered separated from “urge”: the latter, for Marlatt (1985), is an intention that motivates use.

The craving can be “positive”, when the compulsion is seen as a sort of encouragement to the addiction, and so it is like a gratification; “negative”, when addict cares not to feel withdrawal symptoms. It happens because people learn from rewarding experiences, and they want to feel again the same sensation to have a immediate well being sense. The process of learning is strictly correlated to dopaminergic system and neuroscience, that is able to explain why people have a difficulty to stop being addicted.
Also, they become much more sensitive to certain stimuli and this makes them vulnerable. This involves brain changes: the desire for instant gratification would lead to rising rate of dopamine in the shell; the state of emergency (craving), which precedes the achievement of pleasure, increases the rate of dopamine in the core of accumbens.

### 3.2.2 Withdrawal

Withdrawal symptoms are real, especially, for some opiate-like substances, that have the function of inhibiting neurotransmitters and producing analgesia: in fact, when there is an addiction, the activity of glutamate, the neurotransmitter which produces feelings of excitability, is suppressed and to maintain equilibrium, the glutamate system responds by functioning at a far higher level. When there is an interruption of consumption, the glutamate are no longer suppressed and this provokes a phenomenon known as brain hyper-excitability, which results in turn with three kinds of symptoms, that usually change, depending on the case:

- **Emotional symptoms**: like, for example, anxiety, restlessness, insomnia, headaches, depression. All symptoms that affect the emotional sphere, and what determines the personality of the subject;
- **Physical symptoms**: as difficulty breathing, tremor, nausea, vomiting, or diarrhoea;
- **Dangerous symptoms**: like, for example, heart attacks, strokes, hallucinations, delirium tremens, which occur especially when taking drugs or a mixture of the latter.

Obviously, this condition can also cause the insurgence of the other symptoms, called post-acute withdrawal symptoms, which are low enthusiasm, variable concentration, disturbed sleep and others. They can last also years after the interruption of the consumption, it depends on kind of addiction. More is stronger, more lasts the Post Acute Withdrawal Syndrome (PAWS).
3.2.3 Tolerance

One of the major long-term consequences of addiction is definitely the tolerance. When the dependence lasts for a long time, it suffers above all the operation and the balance of the dopaminergic system. Both in animals and in humans has been found that the rate of dopamine decreases and this results in a failure to achieve the initial satisfaction, been pre abuse [27]. In the drug addiction, the tolerance, in fact, is perceived as the need to gradually increase the dose or administration of the drug; in the other types, it is the need to devote even more time to the addiction object.

We can consider the tolerance the last step, during which the addictive behaviour becomes chronic, becoming increasingly difficult to eradicate from the individual. One of the biggest changes, related to drug addiction, just affect the opioid system: receptors gradually become less responsive to the opioid stimulation.

3.3 The role of Neuroscience

At the bottom of addiction, as written in the first chapter, there are basically two phenomena: the compulsion and the withdrawal symptoms. They are caused of other two phenomena, respectively: the neuro-adaptation and the reinforcement processes (that can have positive and negative effects), that contribute to the addictive process and are able to explain also the compulsivity and impulsivity that characterised the addicts.

Impulsivity is defined as the tendency to respond swiftly and gestures unplanned and internal and external stimuli, without worrying about the negative consequences of these same reactions in themselves or others. The compulsiveness can be defined as the implementation of a behaviour despite negative consequences associated with it. The alternation of phases of impulsiveness and compulsiveness will create a complex cycle of addiction, that can be described in this way:

\[ Acquisition \rightarrow Maintenance \rightarrow Withdrawal \rightarrow Relapse \]
3.3.1 The Neuro-adaptation

Neuroscience can help us to understand, largely, the mechanisms that develop in an addiction context. In fact, one of the most important feature of the brain is its neuroplasticity, defined as capacity of brain to evolve, to grow, to learn and, above all, to adapt itself. This mechanism is very essential to the development of behaviour, knowledge and “mind”.

Two important scholars, Charles Bonnet and Michele Vincenzo Malacarne, as long ago as 1783, showed that brain changes are the outcome of external experience, because as a muscle, the brain grows with exercise: neurons (that are the basic units of the brain) become bigger by growing more branches, increasing the connectivity with other brain cells. So, positive intellectual and social activities are able to defend this organ against cognitive deterioration; instead, negative view of the world, like depression, is a sort of unchanging and monotone way that can compromise its mode of operation. Every changes determine how people see the world and how they are, that represents the distinctiveness of single individuals. In effect, as well as brain influences the way in which we see the outside, so people’s behaviours can change the brain, because of its adaptability to new conditions and feelings.

Also in the addiction context, brain changes, but this doesn’t mean that addiction is a disease, it’s just shows that it is a human brain. Citing Thompson: “Addicts may be influenced by their disordered brain chemistry to make bad choices, but they are choices nonetheless”.

The “Stop and Go” theory, seen previously, is central to understand what happens when person engages with external stimulus. Chemical signals between neurons increased electricity: “the ‘yes’ in neuronal communication is when there is a monumental increase in electrical activity (excitation); the ‘no’ is when activity is suppressed (inhibition)” [28].

As concerns the addiction, as we have seen, dopamine governs the reward system and, in particular, the neuroscience concept of “incentive salience”: the feeling of desire and strong need that the brain associate to something, so much that modify
human behaviours. Dopamine receptors in the brain can predict whether a person will find stimulants appealing or aversive.

The reward system is defined like a collection of brain structure, that are responsible for reward-related cognition, including positive reinforcement and both “wanting” (i.e., desire) and “liking” (i.e., pleasure) as defined in the incentive salience model. The alteration of the level of this neurotransmitter is able to influence people’s behaviours. Drugs and other chemical substances are able to change soon the dopamine level and so the state of mind of individuals: in fact, usually people assume these illegal narcotic substances to feel better or disconnected from the world.

A lot of different type of experiences, like sex, food, gamble, and, not only, many drugs, are able to modify dopamine level, that can be considered a “pleasure chemical”. This reaction can alter the brain functionality and so, consequently, modify people’s conduct. Again, the “Stop and Go” theory helps us: when dopamine level is elevated, people, rarely, succeed to stop their impulses. When the goal is near, and so for a addicts, the possibility to reach the addiction object, they feel a sensation of satisfaction because of dopamine level. And so, the reward system lost its equilibrium, upsetting totally individuals and their rational needs.

The neuroadaptation is a phenomenon that intervenes in different stages of the development of dependency, as shown from the Figure 5 [29].
At this concept are associated other two processes: sensitisation and counter-adaptation.

The sensitisation, which often occurs in conjunction with tolerance, is a very frequent phenomenon in individuals to a higher stage of addiction. It is defined as a “a non-associative learning process in which repeated administrations of a stimulus results in the progressive amplification of a response” [30] and it has been studied for the first time by Eric Kandel, a German neuropsychiatrist winner of Nobel Prize in Physiology or Medicine in 2000 for his research in neuronal learning processes. To be involved in the sensitisation is mainly the amygdale: to the increase of dopamine rate is increased stress, which results in the release of the cotropin releasing factor (CFR), a neurotransmitter, both in hypothalamus and in the amygdale.

For counter-adaptation we mean, instead, all those actions that serve to counter the acute effects of addiction, between them we can consider also the tolerance and the withdrawal symptoms, that represent the natural reaction of the body to addiction, to remove or neutralise it. The part of the brain that appears to be most damaged, at this stage, it is especially the GABA system.

### 3.3.2 Reinforcement process

In psychology, there are known two kinds of reinforcement: positive and negative.

By the term reinforcement, it means the probability that a given behaviour becomes habitual or less, according to stimuli associated with it.

A reinforcement is “positive”, if the stimuli act as an incentive and serve to motivate the person to take that type of action. It is defined as “negative”, but if it pushes not to take action for fear of repercussions and punishments.

In the case of addictions, it acts as positive reinforcement, the state of illusion and temporary being, accompanying the addictive behaviour. Instead, it acts as negative reinforcement, suffering, anxiety and low mood you have when trying to quit the addiction.
To give a concrete example, as regards the addiction to drugs or alcohol, the positive reinforcement is linked, as described before, the state of wellness and trance which accompanies the repeated use of substances; negative reinforcement has, on the other hand, the symptoms related to craving and withdrawal.

The drug addict is pushed to abuse substances to receive the positive effects and not to stop, for fear of suffering. The drug and its abuse can reduce the negative feelings related to the use itself, because it becomes a sort of active ingredient for the organism.

Motivated behaviour can be enclosed in three distinctive phases:

- *The phase stimulate*: represents the anticipatory phase, in which the individual is only drawn from the substance and acts to obtain it.

- *The consummatory phase*: in which the individual actually uses the substance, or otherwise puts into action his addiction.

- *The post-consummatory phase*: the phase, in which the first symptoms of abstinence appear.

To be more involved in the reinforcement process, especially the dopamine system: the production of dopamine decreases and hence, the need to increase its degree of dependence to feel satisfied. It acts therefore as positive reinforcement. The neurotransmitters involved in this process are shown in the Figure 6 [29].

<table>
<thead>
<tr>
<th>Dopamine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opioid peptides</td>
</tr>
<tr>
<td>Serotonin</td>
</tr>
<tr>
<td>GABA</td>
</tr>
<tr>
<td>Corticotropin-releasing factor</td>
</tr>
</tbody>
</table>

Figure 6: Neurotransmitters involved
3.3.3 Addiction as a spiralling distress

As shown in Figure 7, realised by Koob, all neurobiological factors that we have previously described, interact with each other, creating a vicious circle, which determines precisely the development of addiction.

![Figure 7: Spiralling distress](image)

Basically, the chemical factors come into play and those reinforcement leading to a cyclical situation of dependence, and a strong vulnerability to relapse.

The human body acts in fact according to the principle of homeostasis, defined as the property of a system, in this case the human organism, to always maintain a balanced situation, whatever the conditions, modified by the external factors, which, therefore, should be balanced continuously.

This process is then associated with the allostasis, for which means the body's ability to adapt, changing. Through change, in fact, the entity seeks to achieve a new stability.

Homeostasis and allostasis, although they seem to be two opposite processes, actually are compensated in various stages of addiction cycle: over the course of transition from drug use to abuse to addiction, both processes are active.

3.3.4 The role of stress in vulnerability to relapse

As seen in the first chapter, stop being dependent is a very difficult process, that much depends on the strength of will and context reference. Recent studies have shown, in fact, that the vulnerability to addiction and the likelihood of spontaneous remission decrease proportionally to the rate of stress, caused by the addiction itself.
First of all stress is a set of emotions and feelings that arise from the interaction of man with the environment: in this sense, can be considered a kind of detector like conditions affect mood of individual, and how this determines his actions. In fact, stress can be both “good” and “bad”. It is good when you need to motivate and encourage the person to ensure that it achieves its objectives; it is bad when, in fact, has a negative influence on the person, suffering, panic attacks, fear of not succeeding, all sensations that also translate into physiological consequences (fast heart rate, lack of appetite and so on).

Stress can be generated from both internal factors and external factors.

The external factors that determine the onset of stress are manifold. The higher levels are reached, especially in difficult situations which are beyond the control features of people, for example in the case of bereavement, separation.

A difficult and considerably stressful environment is among the causes of addiction, but what a vicious circle because stress is amplified by addiction itself.

The dependence, especially when it is at an advanced stage, it can lead people addicted to deprive yourself of sleep, to ignore the stimuli of hunger and thirst, to have economic and family problems.

Instead, the internal factors can be linked both to psychological factors is to stress signals sent by the body itself, the action of stress, in fact, is visible at the cerebral level because it is mainly correlated with the dopaminergic system.

Citing the research of Rajita Sinha, of Yale University: “Brain regions such as the amygdala, hippocampus, insula, and orbitofrontal, medial prefrontal, and cingulate cortices are involved in the perception and appraisal of emotional and stressful stimuli, and the brain stem (locus ceruleus and related arousal regions), hypothalamus, thalamus, striatal, and limbic regions are involved in physiological and emotional responses. Together these regions contribute to the experience of distress” [31].

The landmarks that indicate the presence of high stress are to increase the neurotransmitter CRF and the secretion of cortisol. The neurochemical imbalance
that is reached, has as its main consequence the increase of impulsivity, which does nothing but encourage immediate action, no reasoning, as, indeed, dependence. For this reason, stress amplifies the vulnerability, the propensity to addictive attitudes and the risk of relapse.

By the aforementioned Professor Sinha research emerged two fundamental aspects: the first is that the existing pre-stress as the cause of addiction, it is common especially among young people in adolescence; the second aspect is that stress causes addiction in animals, especially in situations of distress or in isolation. About that studies on rats reveal that: “the direct involvement of dopamine receptors in the reaction to (and memory of) stressful conditions is shown when mice are replaced in the same environment in which they have previously received an electric foot-shock. In this case, the activation of both dopamine receptors (D1 and D2) seems necessary in order to attenuate the conditioned, fear and stress-induced, motor suppression” [32].

The brain, the increased stress causes a further increase in the rate of dopamine in the ventral striatum, just as a reaction to prolonged exposure to the same stress. Excessively prolonged exposure entails, as a result, the occurrence of a situation sensitisation to addiction, which can arise in the development of tolerance and decrease of dopamine levels. The increase of stress, in addition to the vulnerabilities and relapse, are necessarily linked the rise of the phenomena of craving and withdrawal.
4 A NEW ADDICTIVE DISORDER: THE INTERNET ADDICTION

The technology is increasingly seen as evolution and progress, the next step that affects every sphere of knowledge, but, many times, this view is dictated by the enthusiasm for the novelty and is not derived explicitly from an objective judgment on the real benefits that it brings.

This is demonstrated by the many university researches, as for example the study realised from the Valencia University, that analysed the results and consequences had the introduction of technological means in different contexts, from the scholastic context to working one: often, for example, replace the traditional methods of teaching with others that involve the use of multimedia devices did not show clear improvements on the degree of attention of students or a raising of their marks. Yet the technology always occupies more space and a leading position in contemporary society and is, now, hard to imagine not even rely to it to normal routine actions.

Nevertheless both the progress that technology has always attracted humans, both of which have the ability to amplify the senses of men, able to reduce the gap, have more control over their surroundings. The Internet, in particular, began, slowly at first and then more and more pervasive, to revolutionise many aspects of everyday life, which has suffered in recent years many changes. The aspect that perhaps most of all has changed the behaviour of man has been the advent of the Web as a communication medium.

The use of the Internet and its applications is on the agenda and it is virtually impossible to imagine a scenario without it. Precisely because its use is so ingrained, it's not always easy to admit that the technology and its ramifications can be an addiction.

This totalitarian invasion of technology as an essential support for knowledge and everyday life refers to the concept of “adaptation”, theorised by Bernard Stiegler. The philosopher with this concept aims to describe the current tendency of people to trust and fully adapt to the technology, a kind of resignation to the economic dynamics of
Capitalism. The adaptation of this is not to be understood in Darwinian neutral sense, but looks like a real critique of the tendency of man to lose its individuality in order to comply with market rules, without considering other possible solutions. In this sense, also, it is opposed to the concept of “adoption”, where, however, is considered the unstoppable technological process as an enrichment and not a limitation to the possibilities of the individual.

The first works date back to the late 90's when several psychologists, mainly, theorised the internet addiction disorder (IAD).

The first theory about IAD came in 1996 by Katherine Young, while a few years before was Professor Mark Griffiths to have spoken of the technological addiction, for the first time.

These studies can be considered pioneering, because it laid the foundations for the study and analysis of one of the major dependencies of contemporary society. A form of addiction that is still struggling to be recognised as such because of the spread and access the Internet has and for the consolidated role that won.

It is still not considered a dependency in effect because it is fully integrated in the life of every day, unlike other addictions like cocaine or alcohol, which does not have the same kind of approval.

Beyond this, it has been shown that excessive use of technology and the Internet, regardless of the type of declination (social networks, video games, pornography, gambling and so on), producing the same effects on the brain and changes equal to those caused by any other addiction.

The other problem linked to the recognition of this disproportionate use of technology, is the fact that there are no objective criteria to define such behaviour as addictive. The thresholds vary greatly, and for the moment at least, what is considered is mainly the time spent online, daily and weekly.

To spend many hours connected, in their own virtual reality, it has very obvious effects on the mood, because frequently it tends to reduce the hours of sleep to increase those in which you are connected. IAD sufferers also tend to have other
types of addictions (such as for food, drugs or alcohol) or to use technology as a replacement of previous dependencies.

The Internet, thanks to its ability to build a virtual life, parallel to the real one, is seen as a mechanism to escape the daily dissatisfaction. Most people with this type of addiction have confirmed that they have family problems, personal insecurity, problems to relate to others and through a screen you can build an alter ego that reflects the characteristics you would like to have in real life. For this reason, the Internet addiction is seen almost as a form of self-medication: “addicts find pleasant feeling when on-line in contrast to how they feel when off-line”, but is also an illusory and momentary benefits. Instead no-dependent people see Internet only like a tool for personal and business communication.

As described by Sherry Turkle, in her work *Alone Together*[33], Professor at Massachusetts Institute of Technology, people tend to expect more from technology and less from each other, and for this reason new relationships are managed through a computer-mediated communication.

The consequences of a disproportionate use of the Internet are also poured on their academic career and working on that. A study by Young in 1996, showed that 14% of students in the United States, had developed alarming problems to the concentration binders; likewise, many employees were unable to stop using different web applications during office hours.

According to Young there are five different types of Internet addiction:

- **Computer addiction** (i.e., gaming);
- **Information overload** (i.e., web surfing addiction);
- **Net compulsions** (i.e., online gambling or online shopping addiction);
- **Cyber-sexual addiction** (i.e., online pornography or online sex addiction);
- **Cyber-relationship addiction** (i.e., an addiction to online relationships);
In the next few paragraphs will be deepened, especially, three problem among those shown, linked to Internet addiction: gaming, social networks and surfing.

4.1 Video Game Addiction

Video games have been around for a very long time, and yet, only in the last twenty years have made headlines because of their pervasiveness. According to Susan Greenfield, the changes that most affect the risk of developing an addiction are renewed sociability, the ability to create and manage an avatar, the possibility of playing in multiplayer mode, which would be an incentive to those who play to increase the time of use. In particular, the idea of having an avatar created to suit you is a risk factor because the player tends to establish an emotional attachment with the character, because in this way they can fully explore a new identity. Their appeal is that, using them, people can idealise their world and remove much of what is difficult in real life and do many experiences that you would never do in the real world. According the researcher Nicola Lazzaro, there are four items [34] to understand why people became addict to video games:

- Simplify the world;
- Suspend consequences;
- Amplify feedback;
- Set clear goals.

The games are all-encompassing, become completely immersive, because it is to establish a relationship between the individual and the screen. And so, the risk of dependence is strongly correlated to the time spent playing.
### 4.1.1 The consequences of video game addiction

The consequences to the brain are the same as pathological gambling. In fact, the production of dopamine in the ventral striatum is greatly stimulated by the achievement of the goals set at each level of the game. Some studies also have shown a real anatomical change in addicted players: the region of the striatum (one of the dopamine production centres) turns out to be much more extended of the standard. This makes it difficult to determine whether or not there is a predisposition to pathological game or if the anatomical change is the result of brain plasticity. Most likely explanations are both true, because there may be both a genetic predisposition and a subsequent attainment of play skills that change the brain structure.

Play consecutively for a long time and watch the evolution of the same scenario for many hours, repeatedly, they can affect the individual's behaviour.

Even if no correlation was demonstrated between the spread of violent video games and the crime rate, in fact, aggression, control and concern loss are usually related mainly to the desire to play without interruptions and interferences.

The games with a high rate of violence make the subject much less sensitive to violence in the real world, because the brain keeps track of aggression and brutality as common and familiar factors. This has become more evident and dangerous especially with the graphic evolution, more realistic characters, greater strategic challenges and sensory, games appear more vivid and closer to the real context. Thus, the emotions linked to interactivity of the game resulting markedly amplified and this causes it to be also influenced the mood and offline behaviour. The state of confusion that arises is due to the accuracy achieved by the graphic performance of these virtual worlds means that the brain is not able immediately to discern between real and virtual.

The brain of the gamers becomes less sensitive to the environmental factors, to suffer is primarily the amygdala, which is the main responsible for the emotional memory, and that is particularly desensitised. This is also caused by sound and visual effects that characterise the game: the lights and the sounds are very strong for a long draw
the player's attention, actually these sensations, constantly repeated over time, have the effect of reducing the responsiveness of the brain.

Nevertheless, we must acknowledge that there are some educational and simulation games that allow you to gain the skills and analytical skills, especially evident if one compares the frequent player with those who rarely play.

As regards, however, the ADHD syndrome (Attention-Deficit / Hyperactivity Disorder), it is still unclear if indeed the regular game can feed this type of disorder. Recent studies have only shown that children with this disorder are characterised by a greater propensity to play assiduously [35].

4.2 Social network Addiction

The behavioural psychologist Dr. Susan Weinschenk [36] describes in five items how the dopamine release increases when we use social networks:

- *A need of instant gratification*: the possibility to have an immediate answer;

- *Anticipation*: users can also feel satisfied until they have reached their goal, and this depends mainly on the early release of dopamine.

- *Small pieces of information*: the release of dopamine is gradual, because using social networks slowly perceive new information

- *Unpredictability*: the user does not know what to expect, because they do not know what attracts their attention. This state of uncertainty stimulates the reward system and prolongs the enjoyment time.

The curiosity to receive information and immediate responses in the brain produces a positive stimulus of well-being. Users who are more related to the use of social networks, develop an emotional attachment to the platform. And this has had repercussions in the daily life: the idea of perpetual connectivity has revolutionised
the idea of social relationship, people tend to tighten more distant relations, to have many more conversations do not take place as face-to-face, to rethink and revise their idea of privacy.

As for gaming, seen above, also for these applications is the ability to build their own image, not necessarily be the case in real life: the lonely or insecure people are easily able to reverse this trend, becoming much safer themselves and more open towards others. This depends on the possibility of establishing ties and friendships, totally safe thanks to the mediation of the screen. Although it is not allowed complete anonymity, is to create a dichotomy between your online self and your true self, which does not necessarily fit together, remains unchanged because the ability to transmit only certain information about themselves, removing those that deviate from the image that we want to communicate: this is due to the fact that there is, of course, a separation between our public self, our stage, and behind the scenes (the one that we really are). Theory also expressed by Goffmann, when he speaks of the difference between “front stage”, what flaunted in reality, and “back stage” what we really are. Social networks, instead, allow the expression of three personality types [37]:

- **The true self** is the ego expression without social constraints;
- **The real self** is the ego, consistent with the idea that others have of us, through the previous face-to-face contacts;
- **The possible self** is what is shown to the public online.

But, as asserted by Susan Greenfield, “researchers agree that, like, a funhouse mirror, the online self is likely to be an exaggerated version of the real self”, and the greatest risk, in this case, is that this exaggeration could get out of hand. Indeed, the tendency to egocentrism facilitate the engagement in addictive behaviours. The exaggerated ostentation problem is caused by the fact that these platforms stimulate the narcissistic side of the people, tied to obsession to appear: “narcissism is a complex phenomenon that can be broken down into a range of characteristics: exhibition
(showing off), entitlement (believing that one deserves the best), exploitativeness (taking advantages of others), superiority (feeling that one is better than others), authority (feeling like a leader), self-sufficiency (valuing independence), and vanity (focusing of self’s appearance)” [38].

4.2.1 The consequences of social network addiction

To use the social network is a global phenomenon that changed the world in the last ten years and that has led to some significant consequences. A difference of addiction to video games, social networks have many more consequences above all in social life [39], because they tend to involve relationships with others. People mistakenly believe that they can make use of these tools, with no repercussions in reality, but the first consequence concerns the privacy. Indeed, this sense of security, behind a screen, is totally illusory, has the disadvantage to overshadow the problem of loss of privacy, which appears more and more as the price to pay to get a semblance of cyber intimacy.

Another important consequence is the impoverishment of the communication, which is deprived of all its non-verbal aspects. The appearance of reduced face-to-face also produces a limit to the exchange of ideas, whereas many users are passive consumers, who do not communicate their ideas but just only read those of others, with no involvement. The loss of intensity, in this type of communication, it has been shown also to some research: when the conversation is done through instant messages the brain does not produce the same levels of oxytocin, produced during a communication in real time, as the phone or in person. This may also result in a loss of empathy that may or may not have an impact also on offline relationships. The loss of empathy determines, in turn, the loss of emotional intelligence, which means “the ability, capacity, skill or self-perceived ability, to identify, assess, and manage the emotions of the one's self, of others, and of groups”. The change in
communication is not just about the methods, but is also reflected in the language, with the birth of a real language of the Internet.

And finally, another important phenomenon that is catching on with social networks is certainly the spread of cyberbullying: insult, teasing, or ruin the reputation of another person is becoming a form of entertainment. This is mainly due to the fact that, as with video games, through your computer monitor is easy to miss the strength and reality of violence and dehumanise the victim.

4.3 Surfing Addiction

The biggest change implemented by the Internet is represented by the speed and spread of information: any information is easily produced and disseminated on the Web and reach in a short time thousands of connected users. The Web has become a sort of personal memory bank, replacing the collective efforts of family members as a primary source of recall [28], in fact, both Google that other search engines allow access to any type of content.

4.3.1 The consequences of surfing addiction

One of the most important consequences is that users are no longer able to make less to control or retrieve information without the support of Wikipedia or other similar websites. The consequences of this dependence have impact mainly on individuality user, you start to doubt their own knowledge, you are influenced by what they read, because it loses its autonomy of research. This also involves the inability to know how to discern what is right and what is wrong, you have a tendency to believe everything, a trend that has been observed especially among the younger generation, than adults. Among thousands of links, websites, infographics and data, they are especially teenagers to lose the autonomy of research and to completely trust what
they read on the Web, losing their critical spirit and the ability to evaluate information.

Another interesting phenomenon, especially common among young, is the ability to remember more on what site they read the information than the content itself. Probably, this attitude is mainly due to a depletion of memory and in excessive trust in the technology support: the younger generations are content with a rough search, quick and careless, characterised by consultation of a few sources to get only partial knowledge; instead confidence in the material support is determined by their perpetual connectivity, which drives them to constantly search for what they do not know.

It has come to a true saturation of content, even considering that many media products, produced for the web, are completely meaningless and provide no contribution to the user. The “sea of responses” crowding the Internet has helped to change the interaction between the user and the computer: when does a web search, not only activated the brain area associated with understanding and reading, but also the designated areas to control decision making, complex reasoning and vision.

In addition, both the nature of the screen that the new text structures have strongly influenced the mental process of learning. The screen allows, first of all, multitasking and, unlike the book, stimulates more attention to detail, but limits the overall understanding of the text and favours the distraction due to the need of having to continuously scroll the page to read the document entirely.

Hypertext, if on the one hand, stimulates the integration of different sources and materials, on the other hand, is characterised by a continuous deviation from the linear path and can lead to difficulties in the general comprehension. Use continuously browsers search make users less curious, that tend to be less careful and confident, because they became convinced that any information is always at hand, and then they become completely dependent on the electronic instruments.
Even in this case, the dopaminergic system plays a fundamental role: the immediate feedback produces a snapshot gratification, which translates into an increase of dopamine.
5 MATHEMATICAL BACKGROUND

The work proposed here is the result of the union of different research areas. Furthermore to neuroscience and sociological theories, which have been used and widely described in the first part of this thesis, there are two other components, that are essential to study addiction. On the one hand, the mathematical analysis, and in particular, the differential equations, which have the merit to describe the trend of the production of dopamine; on the other side, the computational process, essentially managed using Octave and Java, used to dynamically study the phenomenon of addiction. In addition, before to implement the code, it has been used the automata theory to describe dopaminergic system dynamism.

5.1 Differential equation: formal definition and Euler’s method

Differential equations, and mathematical models in general, have an increasing role in the theoretical study of biological models. They measure the rate of change of continuous variables and so they can have many applications, as for example, to describe theoretically a system and to make predictions about the future evolution of the system under observation.

A differential equation is an equation for a function that relates the values of the function to the values of its derivatives. An ordinary differential equation (ODE) is a differential equation for a function of a single variable [4].

The general first-order differential equation for the function \( y = F(x) \) is written as:

\[
\frac{dy}{dx} = f(x, y),
\]

where \( f(x, y) \) can be any function of the independent variable \( x \) and the dependent variable \( y \).
To solve a differential equation means to find a function $F(x)$ and not an unknown numerical value. In fact, the solution of a differential equation is a function or a class of functions.

If a self-contained formula for the solution is not available, the solution may be numerically approximated using computers.

One of the simplest procedures for the resolution is Euler’s method, member of the Runge–Kutta family, that numerically approximates solutions of first-order ordinary differential equations, with a given initial value. Consider a curve, of which we know only the starting point $A_0$ and a given differential equation that describes it. To find the shape, we can calculate the slope to the curve, and so the tangent line, in the known point $A_0$ and then iteratively repeat the process for each point $A_0 + h$, where $h$ is a very small step. Along this small step, the slope does not change too much, so the curve does not diverge too far from the original unknown curve. In this sense, smaller will be the steps and more accurate will be the curve shape, as shown in the Figure 11.

Nonetheless, one of the limit of this procedure is the necessity to use very little steps, because it is easy to generate approximation errors. An iterative solution rule can be implemented in any programming language, such as C and Java: a smaller step size increases accuracy but also the computation cost, so it is important to consider first the problem at hand to solve.

Euler’s method was used to solve the differential equations of the proposed project in Java programming language, using Eclipse. For Octave, it has been used the LSODE function, as we will see.
5.2 Timed and Hybrid Automata

Automata theory is the study of abstract machines and automata, and it provides a formal language to model the behaviour of real-time systems. In particular, Hybrid Automata are used for the verification and for the specification of features of a dynamic system, which is composed by continuous and discrete components. The continuous component is modelled by a flow condition, such as a differential equation, that governs the change of variables values; instead the discrete component is modelled by jump transitions, that coordinate the transition (or jump) to another state, according to the initial inputs. The system behaviour, in this way, is described as a set of execution sequences, where an execution is a sequence of states or events.

Graphically, an automaton consists of circles (states) and arrows (transitions).

In addition, a Hybrid Automaton includes differential equation, state invariants, transition guards and updates. Some of these ingredients are in the simple Timed Automata, hence before defining Hybrid Automata, we recall the definition of Timed Automata.

5.2.1 Timed Automata: informal definition

A timed automaton is a formal notation to model the behaviour of real-time system over time. The transition from one state to another is controlled by clocks [41], which have the role of coordinating the change of state.

At the start of the execution, the clocks are initialised to zero and their values change with the time, at the same speed. In a timed automaton all terms involved in assignments are constants, and all invariants and guards only involve comparisons of clocks values with constants. Each transition is associated with a time constraint, expressed by a clock: only when the constraint is satisfied by clock value, then it is possible to obtain a change of state.
5.2.2 Specification language for transition systems with timing constraints

To describe a transition system with timing constraints, we can use a graph with a finite set of clocks. The vertices are called *locations* and they are the system’s states; the edges define the changes and they are called *switches*. To each switch is associated a clock constraint, and that switch may be taken only if the current values of the clocks satisfy this constraint. To each location can be associated a clock constraint, called *invariant*, and require that time can elapse in a location only as long as its invariant stays true. Having multiple clocks can be an advantage, because a clock can be set independently of one another.

To define Timed Automata, we have to say what type of clock is allowed on the edge. The simple form of constraint compares the clock value to a time constant, that can be any value from $\mathbb{Q}$ (the set of nonnegative rationals). Let $X$ be the set of clock variables, the set $\phi(X)$ of clock constraints $\delta$ is defined as:

$$
\delta := x \leq c \lor c \leq x \lor \neg \delta \lor \delta_1 \land \delta_2
$$

where $x$ is a clock in $X$ and $c$ in a constant in $\mathbb{Q}$.

A *clock interpretation* $v$ assigns a real value to each clock of the set $X$. The constraint condition is satisfied, if only if $v+\delta$ denotes the clock interpretation for every clock $x$ to the value $v(x)+\delta$.

5.2.3 Timed Automata: formal definition

A timed automaton $T$ is formally defined as follow:

$$
T = \langle L, L^0, \Sigma, X, I, E >
$$
- $L$ is a finite set of states;
- $L^0 \subseteq L$ is a set of initial states;
- $\Sigma$ is a finite set of events;
- $X$ is a finite set of clocks;
- $I$ is a mapping that labels each location $s$ with some clock constraint in $\phi(X)$;
- $E \subseteq L \times \Sigma \times 2^X \times \phi(X) \times L$ is a set of switches. A switch describes the transition from a state to another, specified from $\phi$, that represents a clock constraint.

Each Timed Automaton $A$ is a defined as transition system $S_A$, such that $S_A=(s, v)$, where $s$ is a location (or a state) and $v$ is a clock interpretation for $X$. The initial state is $s$ when $v(x)=0$.

The possible transitions are two: (1) $\textit{elapse of time}$, when for a state $(s, v)$ and a real-valued time increment $\delta \geq 0$; (2) $\textit{location switch}$, when for a state $(s, v)$ and a switch $v$ such that $v$ satisfies $\phi$.

5.2.4 Example of timed automaton: Train-Gate controller

![Timed Automaton example](image)

Figure 12: Timed Automaton example
Figure 12 shows an example of timed automaton, composed of three components: Train, Gate and Controller. The illustrated system operates correctly when the following condition is respected: whenever the Train is inside the Gate, the Gate should be closed. Analysing each label and the clock values, we can note that if the Train is in $s_2$ then the location of Gate should be $t_2$.

The behaviour of the system is correct only thanks to clock role, that coordinate the change of states. Specifically, the label *approach* is immediately followed by the event *in*, but in the Controller between these two events, there are first the execution of the label *lower*, coordinated by guard $z=1$. In fact: “in the location $(s_1, t_0, u_1)$ both clocks $x$ and $z$ have the same value, and hence the event lower with guard $z=1$ is guaranteed to precede the event *in* with guard $x>2$” [42].

### 5.3 Hybrid Automata: informal definition

A hybrid automaton can be considered as a generalisation of timed automata: a timed automaton is defined as a hybrid automaton when for each clocks the rate of change with time is always 1, instead for hybrid automaton the rate of change is dynamic.

A hybrid automaton is characterised by continuous variables (modelled by points in $\mathbb{R}^n$) whose values are determined by a set of ordinary differential equations, that describe the continuous evolution from one state to another. In fact, it is used to describe a dynamical system, composed of discrete and continuous components.

For example, we can consider a hybrid system an automobile engine whose fuel injection (continuous) is regulated by a microprocessor (discrete) [42]. The control mode models the discrete state, while the control switch models the discrete dynamics of controller (defining a change, as determined by a jump condition).

In the linear hybrid automata, we assume that the variables change is constant with time.
5.3.1 Hybrid Automata: formal definition

A hybrid automaton $H$ is formally defined as follow:

$$H=\langle X, V, E, \text{Init}, \text{Inv}, \text{Flow}, \text{Jump} \rangle$$

Where:

- $X$ is a finite set of real-valued variables, defined as: $X=\{x_1,\ldots,x_n\}$, where $n$ is the dimension of $H$; $\dot{X}$ for the set $\{\dot{x}_1,\ldots,\dot{x}_n\}$, that represents the first derivatives during continuous change; $X'$ for the set $\{x'_1,\ldots,x'_n\}$, that represents the conclusion of discrete change.

- $(V, E)$ is a control graph, where the vertices $V$ are the control modes and the edges $E$ are the control switches.

- Initial, invariant and flow conditions: three labels that assign to each control mode $v \in V$ three predicates. They are the conditions associated with continuous evolution of the variables for each state. $\text{Init}(v)$ describes the initial condition, at the start of each state $v$. $\text{Inv}(v)$ describes the possible value during the change state. $\text{Flow}(v)$ represents the differential equation that governs the change.

- Jump condition is a label that assigns to each control switch $e \in E$ a predicate. $\text{Jump}(e)$ represents the transition relation.

The execution of a hybrid automaton is based on a continuous change, that is determined by discrete change (jumps). We can also define:

- $Q$ as the set of possibly infinite states and $Q^0 \subseteq Q$ of initial states.

- $A$ as the set of possibly labels, and for each label $a \in A$, a binary relation $\rightarrow$ on the state space $Q$. Each triple $q \rightarrow q'$ is called transition.

The change can happen in two ways: “(1) by an instantaneous transition that changes the entire state according to the successor relation; (2) by elapse of time that changes
only the values of data variables in a continuous manner according to the activities of the current location” [41]. Each run of a hybrid automaton $H$ can be considered a finite or infinite sequence of states, where at any time instant the configuration is completely determined by the control modes and the values of variables. A hybrid system can be defined linear if any transition relations are linear expressions.

5.3.2 Example of hybrid system: Water level monitor

![Figure 13: Hybrid Automaton example](image)

Figure 13 shows an example of linear hybrid system: the water level monitor. The water level is controlled by a monitor, that continuously supervises the amount of water, turning on and off a pump. The water level changes according to a piecewise-linear function, that is a function whose graph is composed of straight-line sections.

When the pump is on the water level increases by 1 inch per second, however, when it is turned off decreases of 2 inches. In the figure, the water level starts to 1 inch and passes from 5 to 10 inches. The automaton represented is characterised by four states: in $l_0$ and $l_1$ the pump is turned on; in $l_2$ the and $l_3$ is turned off. To specify the
delays, \( x \) has the role of clock: the value of a clock increases with time uniformly and the transition of the automaton resets it to 0 (or it remains unchanged).

### 5.4 Compositionality of Hybrid Automata

Most of the time a hybrid system consists of several components that are coordinated with each other, such that the entire system comportment is determined by the synchronisation of the conducts of the individual elements.

In this sense, an automaton satisfies compositionality if its behaviour can be described in terms of behaviour of its constituting component automata.

Let \( A_1 \) and \( A_2 \) two automata, they can be defined as a product of component system, if their locations are pairs of the two components; the invariants conditions are the conjunctions of the invariants of the component locations; the switches are obtained by synchronising the switches with identical labels.

An example of compositionality is expressed by Train-Gate controller, in Figure 12, where automaton is composed by three elements, the coordination of which allows the proper functioning of the system.

To describe an automaton as the product of more components has the advantage to make a distinction between which events are controlled by the system and which events are controlled by the environment. With these modes it has been realised the automaton of the dopaminergic system, as will be described later.
6 COMPUTATIONAL MODELLING OF ADDICTION

As described in the last chapter, the advent of technology has led to many consequences in the life of man, which over time can also lead to the neuronal changes. In this regard, Susan Greenfield reiterates that: “the generic human brain is capable of very sensitive plasticity that will personalise it into a unique entity”, to emphasise how experiences and external stimuli affect on the brain, which in fact, continues to adapt looking for new impulses. The latter are exactly amplified by technological systems, which like other types of addiction, produce high levels of dopamine.

Sherry Turkle explores better the psychology of human relationships with technology, especially in the realm of how people relate to computational objects. According to her, computer is not only an instrument, but it assumes also a psychological role. “Technology,” she writes, “catalyses changes not only in what we do but in how we think” [33].

Minecraft, Tera, Second Life and World of Warcraft are just some of the online virtual world, that are popular for the particular type of attraction they have on thousands of users, who literally play for hours without any interruption. These people, as told by many reports describing the progress of this type of problem, give up all aspects of their reality for a virtual life, where they believe they have more opportunities for personal development and more opportunities to be what they want. Neglect the family, work, studies, and whatever is external to life within the game: computers are not tools, but part of own social and psychological lives.

Precisely for this reason, for the role played by technology in the people daily life, I have studied previous models on the dopaminergic system to investigate the established relationship between a user and technological object and between two users in a computer-mediated communication.
6.1 Neurocomputational hypothesis and reinforcement-learning

The reason for which the addiction can be described by a computational model is because it can be seen as a dynamic system. Due to some similarities between the dopaminergic system and reinforcement-learning, the second was often used to explain the working of the internal mechanisms of dopaminergic system.

Reinforcement-learning is a machine learning technique that aims to implement systems capable of learning and adapting to the changes of the environment, choosing for each state the action that allows to maximise the reward: “The control problem is modelled as a Markov decision process (MDP). Such a process consists of two functions, R and T, defined over two sets, a set S of states and a set A of actions. The world, under this model, evolves stochastically under a simple, discrete temporal dynamics. At time t, the world is in some state, denoted by the random variable \( s_t \in S \). The agent chooses some action \( a_t \in A \), and the world transitions into some new state \( s_{t+1} \) at the next time-step. […] The transition function T specifies a probability distribution over the successor state \( s_{t+1} \); at each time-step the agent is also assessed some real-valued reward or cost \( r_t \); the probability distribution from which this is drawn is specified by the reward function R” [43].

The transition to the next state is based on the most effective choice of action: based on the received input, the system is able to determine which actions involve a “reward” and which, instead, a punishment.

To associate reinforcement-learning to addiction is very immediate. As described by Volkow [44], addiction involves a pathological change in motivation and choice, and so, with the passage of time, the addict implements his choices to increase the possibility of obtaining an instant reward.

So several researchers have developed computational models to describe the behaviour of the dopaminergic system, in a situation of addiction, based precisely on the reinforcement-learning. In particular, for the proposal work, two models have been considered: the model constructed by the B. S. Gutkin [45] and the model of R. D. Samson [46].
6.2 Gutkin’s Model on nicotine addiction

The Gutkin's model specifically analyses nicotine addiction, focusing on the dosage and duration for the acquisition and persistence of this kind of addiction, in a context of self-administration of nicotine. The idea is to combine “a set of neural circuits at the molecular, cellular, and system levels and accounts for several neurobiological and behavioural processes” [45].

Three processes were considered, that are decisive in the development of addiction: the activity of dopaminergic neurons (DA-neurons), the opponent process (or allostasis) and the increment of interaction between the effect of nicotinic acetylcholine receptors (nAChRs) on the DA neuronal population.

From the psychological point of view, the opponent process is an opposite emotional reaction to a previous stimulus and, in particular, describes the tolerance phenomenon when there are repeated stimuli. For example, in terms of addiction, it describes the reason why impulses are perceived as unsatisfactory, while withdrawal effects (which in this case represents precisely the opposite reaction) are perceived as stronger.

The aim of this model is to unravel the acquisition and the persistence of addiction and to do that, two modules are used:

- **DA Signaling Module**: is the activity carried out by a group of DA-neurons in the interaction with receptors sensitive to nicotine. Briefly, nAChRs receptors increase the production of dopamine, during the administration of nicotine.

- **A-S Module**: represents the physiological activity of the brain (GABA and ventral striatum) and the sensitivity to the different types of impulses. This module corresponds to the learning component of the dopaminergic system.

The interaction between the two modules involves that the activity of dopaminergic neurons is directly proportional to the dosage of nicotine, while brain activity, which
can be described by a differential equation (which will be illustrated subsequently), it remains sensitive to the pulses, representing the level of plasticity that characterises the brain.

As it is visible in Figure 8 [45], the dopamine has a peak and a subsequent decline, which is a putative signature of withdrawal. The activity of nicotinic receptors, particularly sensitive to the presence of nicotine, is compensated by the opponent process, which reduces the dynamism to reach an equilibrium state.

As expected, when nicotine is injected (in this case, with a constant impulse) the DA signal and the activation of the nAChRs show a rapid increase, in the simulation. The constant pulse (chronic administration) causes a consequent decrease in the activity of dopaminergic neurons (slower renormalisation, and so a control level when the nicotine is present), because dopamine to maintain a high level has to resort to more frequent and higher impulses.

After the nicotine removal, the DA activity is dramatically interrupted and, only in the long term, the spontaneous DA activity returns to normal levels. “The tonic DA levels during the short-term self-administration allow the direct activating effects of nicotine. With prolonged self-administration, the influence of the DA signal and the plasticity progressively renormalise because of the opponent process. In the long-term, the self-administration behaviour becomes “routinised”, independent of the hedonic or motivational value of nicotine” [45]. The activation of the receptors, in this particular case those of nicotine, of course depend on the frequency and duration.
of administration. An addictive behaviour is caused by initial mesolimbic changes, motivational, activational and hedonic effects of nicotine.

6.2.1 Gutkin’s model method

This neurocomputational model shows that a short administration of nicotine leads to behavioural motor activation; instead, a long-term activation of the receptors causes a potentiation of the DA signal and this elicits a change in synaptic plasticity that determines the future action choice. Also, a key role is played by opponent process because it reduces the DA response.

This model is inspired by abstract reinforcement learning models of instrumental conditioning. Neuronal activity in the model is described by a differential equation, where S is a sigmoid input–output function, a function that is often used to describe the activation of neurons, and it represents the gain modulation, defined as follow: “a nonlinear way in which neurons combine information from two (or more) sources” [47]. This differential equation represent the DA Signaling module:

\[
\frac{dU_{DA}}{dt} = -U_{DA} + S_{DA} \left\{ \sum_i r_i N(t) \right\}
\]

\[
S_{DA} = \frac{1}{2} \left( 1 + \tanh \left( N(t) \sum_i r_i(t) - \theta_{DA} \right) \right).
\]

Where:
- \( U_{DA} \) represents the neuronal activity, that can assume values in \([0,1]\);
- The \( r_i \) is the effect of an action \( i \) on the DA signal, from -1 (aversive) to 1 (appetitive);
- \( N(t) \) is the nAChR activation with a gain-modulatory effect on \( U_{DA} \);
- \( \theta_{DA} \) is the threshold setting the minimum tonic DA.
On the basis of what is expressed by the differential equation, the value that expresses the activity of dopaminergic neurons is closely related to the sigmoid function. As written previously, the sigmoid function is often used to express the neurological activation, and it returns values between -1 and 1.

In this case, the possible values of $S_{DA}$ are between 0 and 1 and the biological motivation is that 1 is the impulse along the axon, 0 the pulse absence.

Dopamine increases as a function of the stimuli and the activity of nicotinic receptors. If the set of the obtained pulses are greater than the minimum threshold dopamine, then neurotransmitter increases and, in fact, the neutral effect on dopaminergic activity is achieved when $r \neq 0 \land r < \theta_{DA}$. The role of threshold is very important because it is the minimum weight input for which the neuron will send the pulse.

Observing the differential equation, it is also possible to note that the rate of decrease of dopaminergic neurons activity will tend to decline in direct proportion to the value reached. This means that, in the presence of a very strong stimulus, it is very likely to have a peak in neurological activity and this is followed by a rapid decrease in the activity itself. The mathematical model is thus able to show that for obtaining a constant dopamine level, we need to have always stronger and more frequent pulses.

The second module of this model, that concerns about brain plasticity, is expressed as follow:

$$
\tau_A \frac{dU_1^A}{dx} = -U_1^A + S_A(w_{11}^e U_1^A - w_{12}^i U_2^A - \theta_A) + \sigma \xi \quad \text{and}
$$

$$
\tau_A \frac{dU_2^A}{dx} = -U_2^A + S_A(w_{22}^e U_2^A - w_{21}^i U_1^A - \theta_A) + \sigma \xi.
$$

Where:
- $U_i^A$ is the unit activity for each of the action plans;
- $w_{12}$ and $w_{21}$ represent inhibition; while $w_{11}$ and $w_{22}$ represent excitation;
- $\xi$ represents a random input with $\sigma$ as value;
- $\tau_A$ is a constant time;
- \( \theta_{DA} \) is the threshold setting the minimum tonic DA.

This differential equation, unlike the previous one, evaluates the increase of the activity of dopaminergic neurons, considering the weight of the individual activities undertaken. The sigmoid function works in the same way of the previous differential equation, but in this case it is examined the impulses range.

This phenomenon is explained by Hebb’s learning rule [48], that is a neuroscience hypothesis about the adaptation of neurons, and the role of presynaptic and postsynaptic, in the brain during the learning processes.

A synapse is strengthened when a presynaptic input is followed by a postsynaptic neuron response, but the synaptic connection is potentiated when the presynaptic and postsynaptic activation is associated with increased dopamine input, and so only when the gap between the inhibition and excitation is greater than threshold. On the other hand, in fact, when presynaptic and postsynaptic activation is not associated with dopamine input, the connection is depressed.

### 6.3 Samson’s Model: dopamine as a reward signal

Also the Samson’s model is based on the reinforcement-learning, but it is focuses on the role of dopamine as a reward signal [46], in this sense, it is more focused on the role of neurotransmitter in receiving feedback from the environment and the context. This scenario is particularly interesting to capture the processes that affect the body and how the latter interacts with the environment. For this reason, it is studied by neuroscience and psychology. From the biological point of view, however, it is crucial to understand which areas of the brain are involved in human decision-making.
As we can see in Figure 9, “an agent interacts with its environment in order to learn the best actions it must perform to maximise the sum of future rewards” [46].

![Figure 9: Schematic representation of the reinforcement process.](image)

As described above, the reinforcement-learning mechanism is crucial to understand how you develop an addiction, because the dopamine system plays a key role in motivation, which also depends on the considered context.

Already since 1980, several studies have shown that among other characteristics of dopamine, is also to be sensitive to reward predictive stimuli. This means that the activity of dopamine neurons in advance increases even when you expect a reward.

Figure 10 [46] illustrates the activity of dopaminergic neurons.

![Figure 10: Dopamine neurons report a reward prediction error.](image)
As you can see from the scheme, the neurons are activated both when there is a reward and when the reward (although not yet obtained) is predicted.

The activity ends abruptly, however, when the aforementioned reward is omitted. In this case, the function of dopamine neurons is “reward prediction error”: “After learning therefore, DA neurons do not respond to the reward itself, but the difference between expected and received reward” [46]. The introduction of the perception of time and reception of stimuli is fundamental to study both the plasticity factor that characterises the brain and the phenomenon of Stop and Go, that distinguishes the neurotransmitter.

6.3.1 Samson’s model method

In this second model, they used two algorithms: Q-learning and actor-critic algorithms.

The Q-learning is an algorithm for the reinforcement-learning. One of its more important points is the ability to compare the expected utility of the available actions without requiring a model of the environment. It optimises the long term value of performing a particular action in a given state by generating and updating a state-action-value function $Q$, that represents the goodness of an action at a given state.

This model assigns a Q-value for each action-state pair. For an action $a_t$ performed at given state $s_t$, this value can be expressed as follow:

$$Q(s_t, a_t) = Q(s_t, a_t) + \alpha(\delta(t))$$

Where $\alpha$ is defined as learning rate. The Q-learning can be expressed also in this way:

$$Q^{new} (\text{state } (t), \text{action } (t)) = Q^{old} (\text{state } (t), \text{action } (t)) + \alpha\delta (t)$$
The new action-value $Q$ is the result of the old action-value plus $\alpha$, which can be considered a sort of update of the current status.

For each action $a_t$ there is a state change. The aim is to maximise the total reward.

The prediction error $\delta$, that represents the difference between the previous estimate $Q(s_t, a_t)$ and the new estimate after taking action $a_t$, is expressed as follow:

$$\delta(t) = R + \gamma \max_{a_{t+1}} Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t)$$

Where the parameter $\gamma$ represents the temporal discount factor (TD) and specifies how far into the future the agent is concerned with reward. The agent obtains an immediate reward only when at time $t$, the discount factor is equal to 0.

The equation, that describes the model works in this way: when prediction error $\delta=0$, it is null and so the dopamine increases only when the stimulus arrives; when $\delta>0$, it means that there is a prediction, so the dopamine increases even if the stimulus is not obtained yet; when $\delta<0$, it means that the stimulus has been predicted, but it is not arrived.

For the actor-critic algorithm, unlike the Q-learning, the agent is composed of “actor”, which takes action according to its policy and the “critic” that predicts the expected future reward and thereby helps the actor to improve its policy (the agent’s action probability $P(\text{action} \mid \text{state})$, to improve the future reward).

After each action selection, the critic (a state-value function) evaluates the new state to determine whether things have gone better or worse than expected [49].

This algorithm allows to express more accurately the adaptation to changes. The actor updates the policy using the reward prediction error $\delta(t)$ resulting from achieving a particular state. Accordingly, the policy parameter $\pi$ is updated as follows:

$$\pi(s_t, a_t) = \pi(s_t, a_t) + \alpha \delta(t).$$
If the TD error is positive, it suggests that the tendency to select $a_t$ should be strengthened for the future, whereas if the TD error is negative, it suggests the tendency should be weakened. The role of policy is important to describe the development of an addiction, because it represents the inclination to repeat the same behaviour to obtain a greater reward. According to the equation, the policy parameter $\pi$ increases when the prediction error is positive, in fact, supposing that $\delta(t)$ turns out to be positive, that means that the previous action resulted in more reward$(t)$ or a higher-value state $(t+1)$ than usually expected. Then it is appropriate to reinforce the action, and for example to increase the probability of taking the same action again when faced in the same state. Thus the TD error serves as the effective reward signal which takes into account the prediction by the critic.
7 HYBRID MODELLING OF DOPAMINERGIC SYSTEM IN ADDICTION CONTEXT

A hybrid system is proposed, in this thesis, to analyse the mechanisms at the bottom of dopaminergic system in an addiction context. Modelling the dopaminergic system, using hybrid model, allows to study many functions of this cerebral mechanism and its role in the addiction development, isolating the source of pulses to study the possible consequences.

The automata theory has an essential role to analyse complex reactive systems, both in biology and in the neuroscience and, in fact, model checking is emerging as a practical tool. In this sense, the discrete part of hybrid system is represented computationally, instead the continuous part is expressed by mathematical models.

To realise the model proposed here, as written before, they are used two main models: the work of Gutkin and Samson. The Gutkin’s model on nicotine has been the start point to understand the mechanism of self-administration and how the dopamine level changes when there is a constant stimulus; the Samson’s model has been determining to study the gap between the dopamine increment and the achievement of the reward, and so for all the theory of the prediction error.

The proposed model can be considered an extension of the previous models, because in addition examines the behaviour of the dopaminergic system in relation both to environmental factors (determining, according to the latest sociological theories to the development of addiction) and to different types of stimuli (to analyse the dopamine system in different contexts).

To briefly summarise the behaviour of the dopaminergic system, described in detail in Chapter three, we can say that the production of dopamine increases both in the presence of a stimulus and when the stimulus is only expected (but not yet received). The level of dopamine decreases, visibly, when there is an increase or an interruption of the stimulus.

A fundamental element characterising the development of addiction is constituted by the inability of dopamine to return to initial levels if the successive stimuli are no longer strong or frequent. In this sense, the memory is closely related to the
phenomenon of tolerance: the user feels the need to increase the intensity of the stimuli and reduce the intervals between one administration and another. In other words, in the specific case of Internet addiction, the object of study of this work, is what happens when you feel physiologically the increasing need to connect to the Internet without interruption and for more time than before.

7.1 Modelling of Dopaminergic System

This project proposes the model of dopaminergic system as a hybrid system. The starting point is the neurocomputational hypothesis for nicotine addiction by Gutkin, described in detail in the previous chapter, which in this study was modified and simplified.

From the Gutkin’s model, it was derived the differential equation which shows the development of neurological activity, at constant pulse, and it has been conceived another differential equation that, instead, reproduces the accumulation of received stimuli in time, simulating the tolerance phenomenon.

To realise a hybrid system involves various advantages. First, it enables us to isolate and analyse the processes that fully regulate dopaminergic activity. Using the principle of compositionality of hybrid automata, it is possible to separate into distinct and coordinated components the individual elements that interact to neurological level. In fact, the modularity allows to vary the contextual elements, the origin and characteristics of the pulses, to study their effects on dopamine production.

Another advantage obtained is the possibility to abstract the neurological architecture functioning, in order to consider different types and intensity of addiction and not only for nicotine, as in the starting model.

In Figure 14, the hybrid system $A$ describes the dopaminergic system at constant pulses:
- $D$ represents the activity of dopamine and it is expressed as the evolution of variables at continuous state. Its value increments only when $r\geq \theta_p$;

- $M$ represents the continuous variables of memory, that increases when $r>M$;

- $r$ represents the stimulus, its value increases according to $t$;

- $t$ represents a clock, it is associated with the stimulus $r$. When $t<25$, $r=100$;

- $\theta_p$ is the positive threshold, in the simulation is setting to 80;

- $\theta_n$ is the negative threshold, in the simulation is setting to -30;

- $\alpha$ is a fixed parameter, in the simulation is setting to 0.3.

The hybrid automaton $A$ follows closely the operation of the Gutkin’s model. Even in this case, the pulse is administered continuously and at the same intensity for 25 days. Then it is interrupted and in the following days it is possible to notice the same effects caused by abstinence.

The initial state $S_0$ starts with the values set to zero. The jump conditions are associated with clock: when the execution starts, until $t=25$, the stimulus $r$ is
constant (and it is 100). The transition, expressed on edge label, allows to go in state \( S_1 \) when \( r-M \geq \theta_p \), but in the \( S_1 \) the stimulus is interrupted, so the activity of dopaminergic neurons decreases, and when \( M \) increases more than \( r \), physiologically, we are witnessing the phenomenon of withdrawal, in the state \( S_2 \).

### 7.2 Mathematical model of Dopaminergic System

The proposed mathematical model of the dopaminergic system, represented the attempt to insert in the description of dopamine function the contextual factors, that are incisive to development of an addiction. The tools used to implement the model are Octave and Eclipse, that are described successively.

The proposed model is composed by two differential equations:

- *Equation for dopamine signalling* represents the specific neurotransmitter activity in the ventral tegmental area. It is expressed as:

\[
\frac{\partial D}{\partial t} = \alpha (-D + k + \begin{cases} 
1 & \text{if } r - M \geq \theta_p \\
0 & \text{if } \theta_n < r - M < \theta_p \\
-\frac{D^2M}{2} & \text{if } r - M \leq \theta_n 
\end{cases})
\]

The value of dopamine \( D \), between 0 and 1, is calculated by considering the following parameters:
- \( k \) is the constant production of dopamine, such that in the absence of the external signal \( r \), there is a small stable value of dopamine;
- \( r \) is the perceived stimulus;
- \( M \) is the memory, whose value is modelled on the second differential equation;
- \( \alpha = 0.3 \) is a parameter to scale the system dynamics to the time interval considered by Gutkin.
- *Equation for the memory activation* represents the opponent process to dopamine production. When dopamine level increases, also the memory of stimulus is incremented (even if slower) and when the memory becomes stronger than stimulus, the tolerance phenomenon is occurred, that involves the addiction progression.

\[
\frac{\partial M}{\partial t} = \alpha (-M + \begin{cases} \frac{r-M}{2}, & \text{if } r > M \\ 0, & \text{otherwise} \end{cases})
\]

### 7.3 Implementation of model

To solve differential equations they were used in the order Octave and Java. Octave was used initially because it is a numerical analysis software and has therefore already implemented the solving methods, which allowed to study the effectiveness of the proposed equations to represent the behaviour of the dopaminergic system.

The same equations were then solved using the Java language and implementing handcrafted Euler’s method. To use Java, in the second phase, has finally allowed to develop different types of simulations, varying the contextual dynamics and the emission of pulses.

#### 7.3.1 Octave implementation

GNU Octave, that is mostly compatible with MATLAB, is a free software featuring a high-level programming language for the numerical solution of linear and nonlinear problems.

In Octave, the differential equation is written in the form of a vector called xdot(n), where n is only a way to distinguish each expression.
function xdot = f(x,t)
thresholdP = 80;
thresholdN = -30;
k = 0.2;
D = x(1);
M = x(2);
xdot(1) = (0.3)*(-D + stimulus(r(t), M, D, thresholdP, thresholdN) + k);
xdot(2) = (0.3)*(-M + memory(r(t), M));
endfunction

The implementation of continuous part has been done using the function LSODE:

# INITIAL CONDITIONS
x0 = [0.2; 0];
simtime = 50;
t = linspace(0, simtime, 200);
y = lsode("f", x0, t);
plot (t, y(:,1),"-" );
pause();
plot (t, y(:,2),":");

LSODE function needs three arguments: the differential equation, expressed as xdot, the initial condition x0 and the time vector t. In this case, the initial condition is 0.2, because we assume that the initial dopamine value is equal to its constant production, that is expressed also in the equation as k. Two plots are implemented to show the dopamine production and the opposite process of activation memory.

There are two transitions: stimulus and memory. This discrete part is implemented as if-else conditions inside the xdot functions:

function ris = stimulus (r, M, D, thresholdP, thresholdN)
    if (r-M >= thresholdP)
        ris = 1;
    else
        if (r-M >= thresholdN && r-M<thresholdP)
            ris = 0;
        else
            !

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\[ \text{ris} = -M*\text{D}/2; \]
\[ \text{endif} \]
\[ \text{endif} \]
\[ \text{endfunction} \]

\text{function \text{ris} = \text{memory}(r, \text{M})} \]
\[ \text{if} (r>M) \]
\[ \text{ris} = (r-M)/2; \]
\[ \text{else} \]
\[ \text{ris} = 0; \]
\[ \text{endif} \]
\[ \text{endfunction} \]

In the script, to the function \( r \) are associated different kinds of impulses: constant, stronger and more frequent, as we will seen in the next chapter. Below, the \( r \) function implemented in order to obtain a constant pulse in time:

\text{function \text{ris} = \text{r}(t)} \]
\[ \text{if} (t<25) \]
\[ \text{ris} = 100; \]
\[ \text{else} \]
\[ \text{ris} = 0; \]
\[ \text{endif} \]
\[ \text{endfunction} \]

7.3.2. Java code implementation

Java is a object-oriented programming language, which can be used for many purposes. In the proposed work, it was not only used to implement the computational model, but also to perform the simulations (which are explained in the next chapter). Specifically, this language was used for iteratively solving the differential equations with the Euler’s method, to obtain the computational model on which are based all the simulations.

The Euler’s method is linear, and requires only one functional assessment for each time step and gains accuracy by increasing the number of steps. As specified before,
the steps have to be very little, even if the computational cost increases. For brevity, we show only the Java class as it has been implemented for the resolution:

```java
private static void Euler (SystemDop f, int b, double h) {
    double D = 0.2;
    double M = 0;
    double r = 0;
    double k = 0.2;
    int T = 50;
    double time = (T*(1/ h));
    for (int j=0;  j<time;  j++){
        double t= j*h;
        r=f.r(t);
        D=D+(0.3*(-D+f.stimulus(r, M, D)+k))*h;
        M=M+(0.3*(-M+f.memory(r,M)))*h;
    }
}
```

This resolution system is implemented as a Java method, to whom is passed from the main the value choose for the step, specifically $h=0.000001$. This value was chosen precisely to determine the shape of the curve with the minimum possible error.

### 7.3.3 Graphical results

What has just been described is the operation of the basic model of the dopaminergic system. From the computational model, in Java, it has been formed to have the basic structure as a reference for other simulations performed, which will be described in the next and final chapter. This has been implemented considering a constant and lasting stimulus over time, as realised in the Gutkin’s model.
They get three graphs, representing respectively the trend of dopamine and “memory”, in relation to the impulse.

The trend of dopamine, similar to the graph built by Gutkin (Figure 8), shows an initial peak which results in a withdrawal symptom, previous to the interruption of the stimulus itself. Subsequently, the dopaminergic activity is normalised, returning to its constant value. The performance of the memory, however, corresponds to the opponent process, described by Gutkin. In the motivational theory, the opponent process has the function to quiet a previous process, as for instance the reaction to a stimulus, with repeated exposure, the primary process becomes weaker while the opponent process is strengthened.

The memory element has the function of representing the tolerance, that distinguishes the phenomenon of dependence. The tolerance, as previously written, causes the pulse is absorbed and routinised, drastically reducing its perception. Also, from the graph it can be noted that the memory grows much more slowly than the dopamine and has no peaks, but its accumulate counteracts the constant trend of dopamine, causing a spike down.

Figure 15: Graphical results of simulation with constant impulse
8 SIMULATIONS

In order to inquire Internet and technological addiction, we have decided to implement two types of simulations: the first between user and technological object (interpreted as any instrument provided with Internet connection); the second between users in a computer-mediated communication.

Actually, the effects of addiction are basically the same, regardless of the type of dependence considered. To have greater impact on the brain is particularly the repetitiveness that involves a substantial change in the brain, connectible to its plasticity. For this reason, the models described in this chapter are totally abstract and could be applied to many situations of dependency, even completely unrelated to the problem of Internet addiction.

8.1 User-Technological Object simulation

To analyse the relationship that can be established between user and technology object, we have decided to proceed considering different types of pulse: at close frequency pulses and to increasing intensity pulses.

8.1.1 At close frequency pulses

In Figure 16, the hybrid system describes the dopaminergic system with frequent impulses: based on a constant impulse model, described in the previous chapter, the first carried out simulation analyses the situation in which the pulses, originating from a technological object, are frequent and close together in time.

Also in this case the model consists of two components: one that describes the dopaminergic system, which remains totally unchanged, the other which describes the emission of the pulse, which is instead modified.
In the current automaton, the time component has equally two locations $l_1$ and $l_2$: the value of $t$ increases constantly and it is reset at each change of state. The transition from one location to another is taken exactly when $t=0.2$. At every time instant when $t=0.2$, it occurs already the change of state because both locations have the invariant $t<0.2$.

Figure 17 shows results of the current simulation. What it can be immediately noticed that if there are multiple impulses, there is a situation of dependence: dopamine has frequent initial peaks, but, later on, can not achieve the same initial levels, because the stimuli do not increase in intensity. The dopamine trend shows a peak down, index of a withdrawal phenomenon. The memory, that as already described, is the opponent process, increases in relation with impulses.
8.1.2 At increasing intensity and frequency pulses

The aim of the current simulation is to analyse the dopaminergic system behaviour, modifying both the intensity and the frequency of the pulses.
As the previous one, the hybrid automaton in Figure 18 has two components: one represents the dopaminergic system, the other one the impulses emission in relation to time, where time increases constantly, according to the flow condition.

Also in this case, the jump condition is \( t=0.2 \), what changes compared with the previous automaton is the pulse value. For each state change occurs a comparison of the value reached by dopamine and the value of the previous stimulus, represented by the variable “dose”.

The comparison originates three main cases:

- \( r=0 \) if \( D>0.6 \): when the dopamine level is high, the impulses stop at \( t=0.2 \) and the \( r \) value is 0;

- \( r=dose \) if \( D<0.6, \text{Old}_D<D-0.05 \) or \( r=0 \): \( \text{Old}_D \) is the variable that represents the previous level reached by dopamine. As soon as the level of dopamine decreases, and so \( \text{Old}_D<D-0.05 \), or dopamine is decreasing because of absence of impulses \( (r=0) \), the \( r \) value is equal to the previous dose, which is initially 100;
- $r = \text{dose} + 20$ if $D < 0.6$, $\text{Old}_D \geq D - 0.05$ and $r \neq 0$: the $r$ pulse increments ($\text{dose} + 20$) if the previous dose is not enough to maintain a high level of dopamine. This happens because of tolerance, which makes the impulse ineffective.

So, each time the level of the neurotransmitter decreases, the user feels the need to increase the dose and the frequency of the pulses, for maintaining a high dopamine level.

As shown in the results of the simulation, in Figure 19, comparing dopamine, memory and pulses, the user has to inevitably choose a stronger and more frequent pulse to preserve neurological activity.

The effect of tolerance, in fact, reduces both the perceived intensity pulse and the time between one administration and another.

Figure 19: Graphical results of simulation at increasing intensity and frequency pulses
8.2 Communication between users in a computer-mediated communication

In very few years, the impact of technology and social networking has fundamentally changed the way we relate and communicate to others. Susan Greenfield argues that people, especially the younger ones, prefer non-verbal communication, choosing text messages through the Internet to talk to their peers. The choice of adopting a computer-mediated communication has multiple consequences, such as loss of empathy, increase of cortisol, resulting in increased stress, and addiction.

Usually users show a different propensity to this form of communication, which depends mainly from stress, from the sense of isolation and inadequacy, which in most cases results in Internet addiction.

To study this kind of addiction, we have made a simulation which analyses the behaviour of three users (A, B, and C) with different propensity to computer-mediated communication. To simulate a realistic behaviour of the users, we have implemented some Random methods to represent the decision-making factor. For this reason, instead of modelling the system using a Probabilistic Hybrid Automaton, we decided to specify the code step by step.

8.2.1 Simulation code

The simulation was implemented by creating three Java classes: User, Communication and Simulation (the main of program).

User represents the individual who interacts using a technological instrument to send text messages. It is characterised by several methods:
- SystemDop() and Memory() that which respectively return the value of the dopamine and the activity of the memory, and they work as the basic model already implemented;

- SetImpulse() updates the pulse value received from any exchange of messages;

- SetMessReceived(), SetReplyReceived(), SetReplySent(), SetMessSent() store in their respective vectors users who send or reply to messages. This feature is important to be sure that the exchange of messages takes place correctly, and so it allows to know the sender of message to reply;

- Reset() resets pulse and removes all the elements contained in the vectors;

- Random() generates a random number between 0 and propensity factor. It determines the probability to send a spontaneous message or to reply to a received message.

Communication manages the interaction between users, it consists of three main methods, a method Send_Mess(), Reply_Mess(), Impulses():

- Send_Mess(): the user sends a spontaneous message to one of the two other users;

- Reply_Mess(): the user replies by sending an answer to the user from whom he received a message;

- Impulses(): generates the pulses according to the type of interaction performed.

Below, the code of three methods described above:

```java
public void send_Mess(User c1, User c2){
    if (c1.Random() > 0 && c1.Random() < c1.getPropensity()){
        c1.setMessSent(c2);
        c2.setMessReceived(c1);
    }
}
```
public void reply_Mess(User c1, User c2){
    if (c1.getMessReceived().contains(c2)){
        if (c1.Random()>0 && c1.Random()<c1.getPropensity()){
            c1.setReplySent(c2);
            c2.setReplyReceived(c1);
        }
    }
}

public double Impulses(Utente c1){
    if (c1.Memory()<10){
        if (c1.getReplyReceived().size()>0){
            c1.Impulse(150.0);
        }
    }
    else if ( c1.getMessSent().size()>0){
        c1.Impulse(100.0);
    }
    return 0;
}

In the main program, the simulation is run:

- Every time t=0.2, vectors and impulse are initialised to zero by Reset() method and the communication between users starts;

- Since variables are cleared, users can only send a spontaneous message (send_Mess()), with a probability calculated by Random() method, considering their own propensity factor;

- If the user received a message, the SetReplyReceived() is updated and the user can decide whether to answer to the received message (reply_Mess()).

- During the interaction, vectors are updated from time to time, because in this way individuals that take part to the communication are remembered;
The pulses are updated (Impulses()) and according to those which sent and received the dopaminergic activity (SystemDop() and Memory()) is calculated for each user.

As can be noted, sending and receiving are both determined by a probabilistic method, which reflects the propensity to interaction. The choice to use a Random method is dictated by the desire to make the behaviour of the users more realistic and varied, so to imagine situations and different scenarios. In addition, the model works originating of different pulses:

- the reception of an answer (feedback) is equivalent to a very strong impulse so $r=150$;
- the sending a spontaneous message is equal to 100, only in the presence of a medium level tolerance ($M>10$), otherwise it is equal to 0.

In this way, it is most important the received feedback signal than the sending. We took the inspiration for this simulation from the Samson’s model, described in section 6.3. In the model considered, in fact, the presence and the absence of feedbacks influence the dopaminergic activity, that act as “prediction error”.

### 8.2.2 Simulations with different propensity factors

As mentioned previously, the simulations take account of different types of users, according to the factor representing their propensity to interaction. All possible combinations of users have been tested to study the behaviour of the dopaminergic system. For each of them, we have been made 1000 simulations to find the percentage of the time in which one or more users may become addict, and so when their tolerance level is high ($M \geq 15$).
- *Only one user with high propensity:* Figure 20 shows the simulation results with one user (User C) is prone to sending text messages. On 1000 simulations, in 0,02% of cases both the user A and user B become addicts, even having a low propensity. The user C, characterised by high propensity, instead, shows a dependency in 100% of cases.

Figure 20: Graphical results of simulation with one user with high propensity
- Only one user with low propensity: Figure 21 shows the simulation results with two users (Users B and C) are prone to use Internet for communication. On 1000 simulations, in 100% of the cases both the users B and C become addicts, because of their high propensity. The user A, despite of his low propensity, shows a principle of addiction in 45.5% of cases.

Figure 21: Graphical results of simulation with two users with high propensity
Figure 22 shows the simulation results of the interaction between two users, with a high propensity factor (equal to 0.9), and a user with low propensity (equal to 0.2). How is it possible to notice, proof of what is said above, they are frequent phenomena of addiction in users with low propensity factor, if in the group there are at least two users with high propensity.

Figure 22: Graphical results of simulation with two users with high propensity
- **Three users with high propensity**: Figure 22 shows the simulation graphic results when all the users are prone to use Internet for communication. On 1000 simulations, in 100% of cases all the users become addicts, because of their high propensity.

![Graphical results of simulation with three users with high propensity](image)
- *Three users with low propensity*: if there are three users with low propensity to interaction, the dopaminergic activity is very low and slightly exceeds the constant production threshold \((k=0.2)\). Consequently, there have been no cases of addiction.

![Graphical results of simulation with three users with low propensity](image-url)
Basically what emerges from the simulations is that what mainly affect the performance of the dopaminergic system is the propensity to use technological means to communicate with other users. In this sense, the propensity factor can be considered a kind of parameter that identifies the individual need to feel part of a group, to receive instant feedback signals, to combat a sense of social isolation.

In fact, according to Susan Greenfield: “individuals with high levels of anxious attachment used Facebook more frequently. […] The posting and receiving of entries on Facebook or Twitter could trigger the release of small blips of dopamine, possibly encouraging such activity to become not only rewarding but also compulsive” [28].

It is interesting to notice that the statistics on simulations show that the percentage of addiction increases especially when multiple users have a high propensity factor, as we can see in Figure 22.

This may demonstrate that the sociological phenomenon whereby, among peers, prevails the principle of imitation. This last aspect, in particular, may confirm the importance of social and environmental factors relating to origin and development of an addiction. As specified in section 2.2, in fact, the elements which affect the spread of an addiction are consensus, consistency and distinctiveness, which specify exactly how this addict behaviour is considered within the society and how the same social dynamics facilitate its diffusion. Therefore to communicate and relate with people with the same addiction also tend to alter our conduct, because it would change the way we perceive a behaviour.

For completeness, some simulations were performed considering the presence form the very beginning of one or more addicted users (and so with a high tolerance level). From the results obtained, it can be said that the greatest impact on the development of an addiction is primarily propensity sociological factor, more than the level of tolerance that does not involve significant changes.
CONCLUSION AND FUTURE WORK

The aim of this thesis propose a computational framework for the study of addiction, taking into account both neurological and sociological characteristics.

To achieve this, we decided to proceed gradually, to fully understand the complexity and dynamics of the phenomenon.

Starting from the theories of the French philosopher Bernard Stiegler, we framed the dependence from an “external” point of view, reconstructing the figure and the role of the addict in today’s society.

Later, we moved on what are the effects of addiction on the brain and the dopamine system, and we have tried to study its dynamics in detail. Inspired by Gutkin’s and Samson’s models, we have created a simplified modular model of the dopaminergic system, using the theory of Hybrid Automata.

This allowed us to develop a hybrid system consisting of two components, the dopaminergic system and a impulses generator, in order to dynamically grasp the trend of neurological activity, in relation to many environmental factors.

After a general overview we have decided to focus mainly on Internet Addiction because it is an unexplored phenomenon, that have many sociological and psychological implications.

Linked to this, we have done some simulations, exploring the relationship between a user and a technological object, between three users in a computer mediated communication.

This new approach to the study of addiction has led to numerous and enthusiastic results, that make us even more hopeful for future developments.

First, using Hybrid Automata, we got a completely abstract dopaminergic system model, which is able to represent all types of addiction, unlike previous models, in which it analyses the dopaminergic activity in relation to a single type of pulse.

We were able to analyse, though still partially, the subjective aspect of addiction, developing an individual’s decision making component and giving a decisive role to environmental factors, totally neglected in previous models.
Finally, through the simulations, we played one of the phenomena underlying the spread of an addiction: the principle of emulation, which leads individuals to embrace a behaviour to feel accepted in the peer group.

Of course, this project is still in its infancy and can undoubtedly be further refined and improved.

With the same approach, several kinds of other studies can be carried on: neurological structures can be developed to study other brain processes; a network of individuals could be built to study how long it takes to an addiction to be spread; finally, there are numerous advantages to be gained by studying carefully other subjective factors of the addiction, to capture the unexplored aspects of dopamine.


