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Addressing the complexity of climate change through games

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Abstract

Climate change is one of the main issues of our time and the Intergovernmental Panel on Climate Change has declared the state of global emergency. Although a recent report reveals that the 93% of Europeans see climate change as a serious problem, it seems the issue is not recognized as so urgent by individuals or as something that can be tackled through individual actions. Towards the vast complexity of the phenomenon, the individual feels distant and impotent attributing the main responsibility of implementing effective actions to governments and industries.

We believe the change of public attitude at a larger scale is as relevant as the utmost necessary governmental action plans. The present work addresses the topic of climate change in order to encourage the commitment of ordinary people to take care of the environment, enhancing the role that each individual can have locally to impact globally.

The thesis focuses on climate as a complex system and tackles specifically the need to master the concepts and mechanisms typical of complexity as a way to foster conscious pro-environmental actions through science education.

It is considered relevant the impact on educational approach to forge in the public an adequate mindset oriented towards a new causal logic where the concepts of complexity – such as emergent properties, feedback mechanisms and deterministic chaos – are cognitively accepted and embraced. Amongst the didactic tools developed by researchers in science education, the work focuses on four role-playing activities that have been analyzed in details, in particular to show how the concepts typical of complexity can enhance the role of individuals to tackle the issue of climate change. Indeed, the educational path proposed in this thesis was designed with the big scope to contribute to make people believe in the power of individual actions towards the global change comprehending the true aspects of complexity.

Sommario

Il cambiamento climatico rappresenta una minaccia nei confronti dell'umanità e di molte altre specie, tanto che l'IPCC (Intergovernmental Panel on Climate Change) ha dichiarato lo stato di emergenza globale. Un recente report della Commissione Europea afferma che il 93% degli europei percepisce il cambiamento climatico come un problema grave, ma sembra che non vengano riconosciute nè l'imminenza delle conseguenze nè la possibilità che azioni individuali abbiano un effettivo riscontro sull'evoluzione del fenomeno. L'individuo si sente impotente di fronte alla vasta complessità del fenomeno del cambiamento climatico, e attribuisce ai poteri forti, quali i governi nazionali e le potenze industriali, il compito di affrontare il problema.

Pensiamo che al fine di affrontare il cambiamento climatico, oltre all'adozione di appropriate strategie a livello nazionale ed internazionale, sia necessaria anche un nuovo atteggiamento da parte dell'intera popolazione. In questa tesi si intende affrontare il tema del cambiamento climatico e della necessità di incoraggiare l'impegno del singolo nei confronti dell'ambiente, sottolineando l'influenza che l'azione locale individuale esercita sul sistema climatico a livello globale.

La tesi parte dal presentare il clima come sistema complesso, e in particolare si concentra sul fatto che la comprensione dei meccanismi alla base del suo funzionamento sia utile per incentivare azioni consapevoli e virtuose nei confronti dell'ambiente.

Al fine di permettere la comprensione della complessità del sistema climatico, si considera importante fornire una nuova logica causale con la quale è possibile cogliere il significato di concetti tipici della scienza dei sistemi complessi, come le proprietà emergenti, i meccanismi di feedback e il caos deterministico.

Nella tesi vengono proposti i giochi di ruolo come strumento didattico utile per introdurre alla scienza dei sistemi complessi, e in particolare vengono analizzate quattro attività al fine di mostrare le loro potenzialità nel presentare alcuni concetti legati alla complessità. Si ritiene che le attività proposte possano contribuire a fare comprendere ai partecipanti l'effettiva influenza che il singolo esercita su un sistema di dimensioni globali.

Ai miei nonni

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Introduction

Climate change is one of the main issues of our time, its probable effects threatening ecosystems and our own lifestyle and well-being, as well as most likely impoverishing water and food resources with the possible consequence of incrementing poverty and violent conflicts. The IPCC – Intergovernmental Panel on Climate Change, created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) with the aim of assessing *"the state of scientific, technical and socio-economic knowledge on climate change, its impacts and future risks, and options for reducing the rate at which climate change is taking place"* (https://www.ipcc.ch/about/) – has declared the state of global emergency due to the phenomenon of global warming, listing the different possible outcomes and stating it is necessary to tackle the issue in order to avoid irreversible consequences (IPCC, 2018). Also, it has been declared that it is virtually certain that the present global warming is mainly due to human activities, especially through greenhouse gases emissions and land alteration: it has been estimated that human activities have caused the increase of the global mean temperature of approximately 1.0°C with reference to the pre-industrial levels, and *"global warming is likely to reach 1.5°C between 2030 and 2052 if it continues at the current rate"* (IPCC, 2018) – that is approximately 0.2°C per decade.

In 2015, in the Paris Agreement it was agreed by 195 countries to pursue efforts to limit global warming to 1.5°C – a threshold that has been indicated by the IPCC as having consequences to which humanity is still likely able to adapt, and that also represents the best scenario: as a matter of fact, anthropogenic emissions up to the present *"are unlikely to cause further warming of more than 0.5°C over the next two to three decades (high confidence) or on a century time scale (medium confidence)"* (IPCC, 2018). The IPCC stated that in order to limit global warming to 1.5°C, global net anthropogenic CO_2 emissions should decline and reach net zero by 2050: this is possible only through *"rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial system"* (IPCC, 2018). However, the latter requirement poses profound challenges, for example transitions in land use include the reduction of non-pasture agricultural land for food and feed crops – as well as pasture land – in favor of agricultural land for energy crops and forests, but *"the implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological,* *financing and environmental barriers that differ across regions"* (IPCC, 2018). Some improvements have already been made, but much is still to do: for example – as far as the energy system is concerned – solar energy, wind energy and electricity storage technologies have improved over the past few years, however in order to limit global warming to 1.5°C the necessary investments in low-carbon energy technologies and energy efficiency are estimated to be *"upscaled by roughly a factor of six by 2050 compared to 2015"* (IPCC, 2018).

What could induce national governments to do better – while acknowledging the barriers – is the awareness that tackling climate change is necessary to provide security to populations, by avoiding both the increase of extreme weather events and the threat to food and water sources. In addition, the implementation of pro-environmental policies can be enabled or inhibited by public acceptability (IPCC, 2018), thus *"it matters a great deal what public think, and what actions they consequently support, or are willing to undertake themselves"* (Norgaard, 2006). Public opinion polls often show that people do care, and do want something to be done: as far as the European Union is concerned, a survey on people's opinion on the seriousness of the climatic issue suggests that in 2019 climate change *"has overtaken the rise of international terrorism, and now ranks as the second most serious problem after poverty, hunger and lack of drinking water"* (EC, 2019). EU citizens see national governments as having a primary role in tackling climate change, and approximately nine in ten think that effective strategies should be adopted in order to increase the amount of renewable energy used and to reduce greenhouse gases emissions *"to make the EU economy climate neutral by 2050"* (EC, 2019). Also, EU citizens are increasingly taking action to fight climate change, for example by regularly using environmentally-friendly alternatives to their private car, reducing waste, and cutting down consumption of disposable items (ibidem). However, those individual actions are effective only if perpetuated and if sustained by policies adopted by governments and industries, which represent a major leverage on the future behavior of the climate: people should be encouraged both to keep undertaking individual actions, and to support the adoption of pro-environmental policies by governments. Providing information on the consequences of climate change is not enough for inducing effective behavior (Norgaard, 2006), since people encounter difficulties in understanding how the actions they undertake individually – as well as their individual support for certain policies – can have impact on a phenomenon that is global, and that the effects could be seen far in the future. Succeeding in the shifting from concern to effective action is then influenced by the understanding of the complex causal mechanisms governing the behavior of climate as a complex system (Tasquier & Pongiglione, 2017; Jacobson et al., 2017; Roychoudhury et al., 2017). Indeed, several research in the field argue that the willingness to spread effective information on climate change can be translated into the necessity to provide knowledge about complex systems. A question arises if it is actually possible to teach complexity: traditional methods – analysis of specific complex systems through reproduction of the latter in a laboratory – cannot be exploited because of the complexity of the systems' structure and of the large time scale in which certain behaviors are displayed. However, it has been stated by researchers in the field that it is actually possible to teach concepts linked to complexity exploiting innovative methods (Wilensky & Resnick, 1999). The latter are computer-based didactical programs that simulate complex systems, giving learners the possibility to focus on the behavior of their single elements and on the relations among them: no real complex system is simulated, but through the definition of rules for the behavior of the elements, certain macroscopic properties are displayed and users have the chance to make sense of the concepts of emergence and feedback.

Another didactical tool that has been developed to give learners the chance to experience the causal mechanisms governing the behavior of complex systems, is the design of role-playing activities: participants are asked to act as elements of a complex system, and as a result they have the possibility to make sense of the emergence of macroscopic behavior. In the present work we propose four role-playing activities – selected from different sources – that can help to highlight some important concepts of complexity, and in particular the fact that each individual behavior of an element of a complex system exerts influence on both the other elements and on the macroscopic properties.

The focus of the first three activities is on the concepts of emergence, self-organization, feedback, and attractor. In the last activity, participants are led to the awareness of the necessity to adopt strategies when dealing with complex systems in order to reach a certain result: variations in a complex system's behavior happen over an extended time scale, thus a long-term plan is important to achieve the wanted configuration for the system.

The understanding of the concept of emergence is important because it is strongly linked to the non-linearity of the relations among the system's elements: participants become aware of the necessity to abandon reductionism, and they can make sense of the feature of complex systems of being strongly sensitive to perturbations. Participants are thus led to understand how their individual actions actually exert influence on the climate system. The concept of self-organization can help in this sense, because it is linked to the fact that in complex systems there is no central control and the macroscopic behavior is displayed as a consequence of relationships among elements, and of the fact that the elements gradually adapt to a variation in one's behavior: the more frequently a certain action is performed, the more likely it is to have a consequence on the system as whole. The concept of feedback is necessary for a complete description of a complex system's structure, and to understand how processes of inhibition of certain phenomena can be inducted, as well as how small variations in the climate at the present time could have catastrophic results.

Finally, climate as a long term average of meteorological patterns is challenging for people to understand, as it is highlighted by the fact that people encounter difficulties in considering that *"an increase in the average temperature of the Earth does not mean a higher temperature everywhere"* (Roychoudhury et al., 2017). The concept of attractor can help to explain the necessity to use statistical tools to study the climate.

The present work is divided into three chapters.

In the first chapter, a brief description of the phenomenon of climate change is provided, as well as the possible future scenarios the IPCC have presented in order to predict the dimensions of the problem humanity will have to face if no effective strategies are adopted to mitigate global warming. The complexity of the climate system is highlighted, and an overview of the models designed by climatologists to overcome the difficulties encountered in the study of such a complex system is provided.

In the second chapter, the general characteristics of complex systems are briefly presented, and it is stated that it is necessary to abandon reductionism and determinism and to adopt a new scientific approach in order to analyze complex phenomena.

Despite the necessity of a scientific approach that is different to the one that is traditionally taught in schools, it is reported that it is actually possible to make learners grasp some important features and concepts of complexity through innovative teaching methods.

In particular, our interest is on role-games, through which participants can actually get into a complex system and thus experience the mechanisms through which a surprising macroscopic behavior can emerge from very different behaviors of the system's elements.

Finally, in the third chapter four role-playing activities are described and analyzed as being useful to highlight some features of complex systems. The description of the rules of each activity is followed by a brief introduction to a possible debrief on the game, that would help participants to understand the mechanisms governing both the game and complex systems in general.

The four role-playing activities were selected starting from different sources and were re-adapted according to the aims of this thesis. The collection of the four activities represents an educational path designed by the author of this thesis with the intent to explore how a game-based approach toward complex systems can foster both understanding and engagement with respect to the theme of climate change. The detailed analysis of the activities – presented in chapter three and aimed at highlighting the different roles complexity plays in each game through its peculiar conceptual aspects – is the main original trait of this thesis.

Chapter 1
Climate change: an overview

In this chapter, we address the issue of climate change, looking at different aspects of the science related to it. Specifically, the chapter is structured as follows: in the first section, the focus is on the state of knowledge on climate change that is assessed by the IPCC; then – acknowledging that a correct perception of the causal mechanisms characterizing climate change is required to induce effective pro-environmental policies – in the second section we provide a brief description of the climate as a complex system; finally, in the third section, we describe two kinds of models designed by climatologists.

1.1 The IPCC and the state of the art on climate change

According to the Intergovernmental Panel on Climate Change (IPCC), climate change represents an unprecedented global emergency. This organization was created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) and is the main authority on this topic. Periodically, IPCC scientists prepare "comprehensive Assessment Reports about the state of scientific, technical and socio-economic knowledge on climate change, its impacts and future risks, and options for reducing the rate at which climate change is taking place". IPCC assessments and special reports are prepared by three Working Groups (WG), each aiming at gathering information on a different aspect of the science related to climate change. The IPCC Working Group I (WGI) examines the physical science basis of the phenomenon, combining observations (direct data), paleoclimate – through the analysis of sources indirect data name proxy –, process studies, theory and modelling. Working Group II (WGII) assesses the impacts of climate change, it considers the vulnerabilities of both natural and human systems, and their capacities and limits to adapt to consequences of the changes occurring in the climate system. Finally, the IPCC Working Group III (WGIII) looks at the aspect of climate change mitigation, which involves actions that reduce the rate of climate change: the main goal of IPCC is not only to enhance knowledge on the topic within the scientific community, but also to provide governments at all levels with information they can use to develop climate policies. In this chapter, we will often refer to IPCC reports to present relevant research results that constitute the state of the art in the field of climatology.

The main evidence of climate change occurring, is the warming of the climate system, that is to say the increase of the temperature of the atmosphere, land, and oceans – the warming of the latter dominating *"the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010"* (IPCC, 2014). Other evidences of climate change that have been observed are the increase in precipitation, changes in the ocean surface salinity and consequently in the global water cycle over the oceans.

The increase in global temperature have resulted in many consequences such as ice sheets losing mass, glaciers shrinking almost worldwide, and the increase of permafrost temperature. As a result, sea level has risen, at a rate that – since the mid-19th century – has very likely been *"larger than the mean rate during the previous two millennia"* (IPCC, 2014). Also, the pH of ocean surface water *"has decreased by 0.1, corresponding to a 26% increase in acidity"* (ibidem).

In the Fifth Assessment Report by the IPCC, it has been stated that it is *"95% certain that humans are the main cause of current global warming"* (IPCC, 2014), through greenhouse gases emissions and other anthropogenic forcing together. Carbon dioxide concentration in the atmosphere, whose increase has been proven to be a cause for global temperature rising, has reached a value that is *"unprecedented over the past 3 million years"* (Willeit et al., 2019), and anthropogenic greenhouse gases emissions have continued to increase *"despite a growing number of climate change mitigation policies"* (IPCC, 2014). The IPCC warned on the many irreversible consequences that humanity will have to face if emissions do not reach net-zero. As a matter of fact, *"the climate will keep slowly warming for around ten years after CO_2 emissions stop due to thermal inertia"* (Ricke, 2014).

Observed changes in the climate have impacts on natural and human systems, for example *"changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality"* (IPCC, 2014), ocean acidification affects marine ecosystems, and the increase of extreme weather and climate events – such as heat waves, droughts, floods, cyclones and wildfires, that have been observed since about 1950 – will very likely cause a rise in migration of populations.

The worsening of extreme weather and its consequences on humanity and human rights cannot be avoided but only mitigated, and this is possible only if strategies of mitigation of, and adaption to climate change are adopted both by governments and citizens in their everyday life.

The IPCC not only describes and interprets causal links between past trends and the present situation, but also elaborates predictions on future changes in the climate, considering four different 21st century pathways of greenhouse gases emissions and atmospheric concentrations, air pollutant emissions and land use. Those are named Representative Concentration Pathways[1] (RCPS) and include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5) (IPCC, 2014). Under all assessed emission scenarios, *"surface temperature is projected to rise over the 21st century"* (ibidem), heat waves and extreme precipitation events are very likely to occur more often, as well as the ocean will continue to warm and acidify and global mean sea level to rise.

This particular kind of prediction – named projection – do not consider only the environmental dimension but evaluates also impacts of climate change on natural and human systems. In particular, reports show that *"a large fraction of species faces increased extinction risk"*, and *"climate change is projected to undermine food security"* and *"to reduce renewable water and groundwater resources in most dry subtropical regions"* (IPCC, 2014).

Even though global economic and social impacts from climate change remain difficult to estimate, it is very likely that erosion of food security, reduction of water availability, and major exposure to extreme weather events will result in increase of poverty, displacement of people and risks of violent conflicts (IPCC, 2014).

The IPCC Assessment Reports state the necessity of climate mitigation and adaption policies in order to limit the effects of climate change. The design of effective climate policies is possible only if a correct perception of the phenomenon of climate change and understanding of the climate system as including many factors and intertwined relations is reached.

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[1] The RCPs are labelled after a possible range of radiative forcing values in 2100 (respectively 2.6, 4.5, 6.0, and 8.5 W/m^2. The different RCPs are based on diverse assumptions on the collocation of the peak of emissions in the future: the latter is assumed to occur between 2010-2020 in RCP2.6, around 2040 in RCP4.5, and around 2080 in RCP6.0, and in all the latter three RCPs emissions are supposed to decline after the reaching of the peak. On the contrary, in RCP8.5 emissions are assumed to rise throughout the 21st century.

Climate can be defined as the *"statistical description in terms of the mean and variability of relevant quantities over a period of time"* (IPCC, 2014) that is classically considered as 30 years by the World Meteorological Organization.

The quantities that need to be studied in order to analyze the atmosphere and the climate are many, for example temperature and pressure at different heights in the atmosphere, direction and speed of wind, humidity, precipitation, temperature at the surface. Climate variables data have to be collected in many different spots, both on the surface of the Earth and at different heights in the atmosphere.

The kind of instruments available to climatologists have of course changed over the years, and their reliability has gradually increased. Climatologists have collected data since the XVII century, when the barometer was invented as well as other instruments. However, during the first centuries in which interest was directed to the atmosphere and to the climate, data were collected only in a few spots, while now a dense net of data collectors makes it possible to analyze the system globally.

One question climatologists want to answer is how the climate have changed over the years, and the climatic history has been actually reconstructed through the analysis of indirect sources of information. The indirect sources of climatic information are also called *proxy* and are actual natural archives, such as Antarctic ice coring, analysis of coral features and of the rings inside trees. The knowledge of processes that resulted in a certain proxy helps making hypothesis on how climatic variables such as global temperature and carbon dioxide concentration varied over the years.

For example, measures of carbon dioxide concentration in air bubbles trapped in diverse layers of ice allow the reconstruction of the variability of carbon dioxide concentration in the atmosphere in that specific geographical area over time.

In the graph in Figure 1.1, it is shown how both proxy data and measures of climate quantities are necessary to reconstruct the variability of a climate variable such as global temperature. In particular, the physical quantity represented in the graph is the main index in the study of climate change, i.e. the anomaly of the Global Mean Surface Temperature (GMST), that is the difference between GMST in a certain year and a mean value $GMST_{ref}$ evaluated in a period of reference, that is usually 1961-1990:

$$Global\ Temperature\ Anomaly = GMST - GMSTref$$

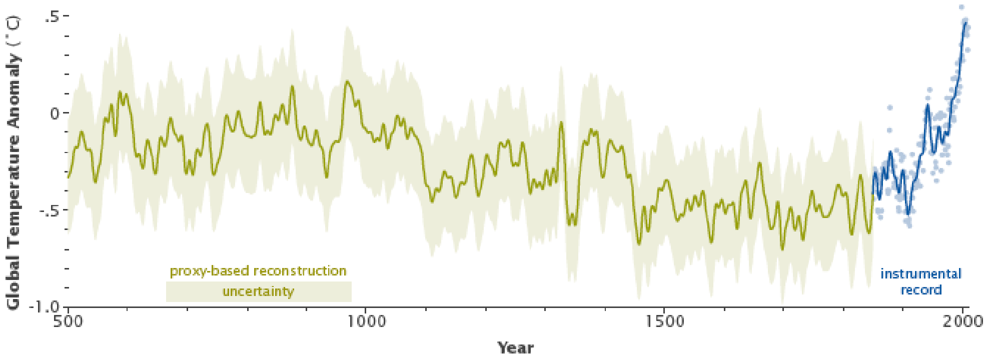

Figure 1.1: Global Temperature Anomaly over the last 1500 years (figure taken from https://earthobservatory.nasa.gov/features/GlobalWarming/page3.php)

The data represented in the graph in Figure 1.1 suggest that the global temperature is now higher than it has ever been in the past 1000 years. Also, it is clear that variations in the global temperature have always occurred on a temporal scale of years or decades, and those are definitely due to natural forcing[2], such as volcanic eruptions and variations in the value of the solar constant.

The rapid increase in global temperature in the last century made climatologists suspect a global warming is occurring, but this is not enough to conclude the phenomenon is caused by human activities. In order to identify the causes of the recent global warming, it is necessary to define the main mechanism that controls the temperature of planet Earth, that is radiative balance.

Indeed, the temperature of the Earth is the result of a dynamical balance between the flux of energy coming from the Sun and that radiated by the Earth. The average temperature stabilizes around the value T that allows the Earth to emanate a flux of energy that is equal to the quantity absorbed.

The ratio of flux of solar energy that is reflected by clouds, aerosol, ice, oceans, and soil, is called the *albedo*. Every process – radiative forcing – that results in a variation of the albedo determines a perturbation in the energy balance between the Earth and the Sun, and thus a variation in the temperature of the Earth. A radiative forcing is said to be positive if it determines a temperature increase, while it is negative when it results in a decrease of temperature.

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[2] According to the IPCC, *“external forcing refers to a forcing agent outside the climate system causing a change in the climate system”* (IPCC, 2014).

Variations in atmospheric concentration of a number of gases called greenhouse gases (carbon dioxide, methane, water vapor, nitrous oxide) are radiative forcing as well: greenhouse gases molecules absorb the radiation emitted by the Earth, not allowing its escape from the atmosphere, and causing the warming of the latter. As a consequence, the increase of greenhouse gases concentrations represents a positive radiative forcing. The graph in Figure 1.2 shows the variations in the concentration of methane and carbon dioxide over the years and suggests that those are strongly correlated to the variation in global temperature.

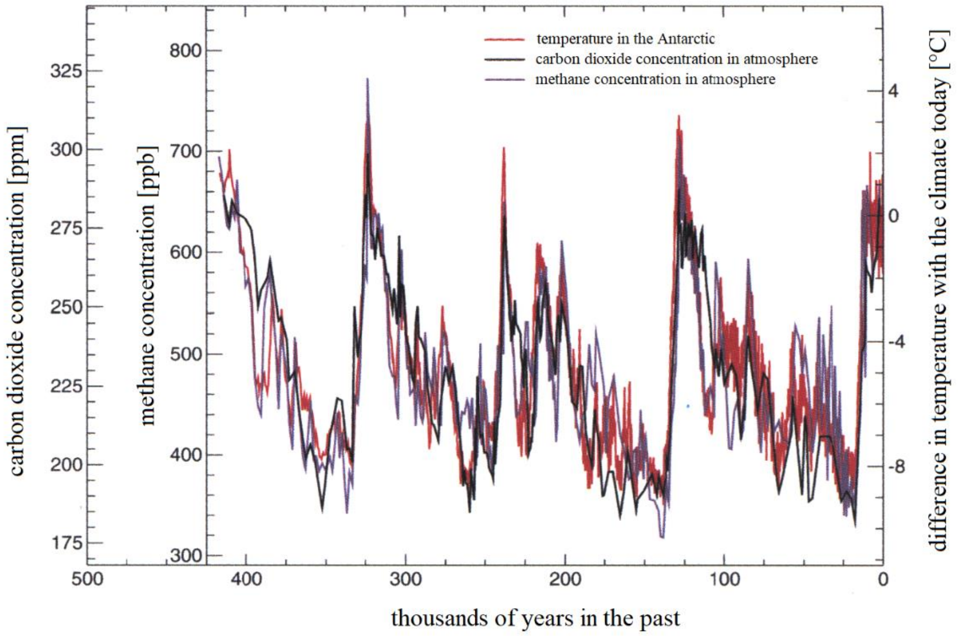

Figure 1.2: comparison between temperature, carbon dioxide concentration, and methane concentration over the last 500 thousands years (Pasini, 2003)

1.2 Climate as a complex system

It has been stated above that the climate variables that influence the radiative balance between our planet and the Sun, and that thus determine the variation in the global temperature, are many. Also, the relations among the climate variables are intertwined and cannot be described by means of linear differential equations. What makes the study of the behavior of the atmosphere and of the climate even more complicated, is the presence of feedback[3] mechanisms.

The climate system is comprised of many subsystems that are intertwined, and which interactions and feedback mechanisms have to be considered in the analysis of climatic phenomena. The atmosphere, that represents the main focus of climatic studies, is an open system since it is in continuous interaction with the soil, the oceans, the Sun, and the internal structure of the Earth: for example, the analysis of the oceans is vital to understand the mechanisms governing the dynamics of the atmosphere, since the oceans are able to reduce the amount of carbon dioxide in the atmosphere, but also a greater global temperature determines a greater amount of water vapor – a greenhouse gas – in the atmosphere resulting from evaporation. The process through which the oceans help in reducing the amount of carbon dioxide in the atmosphere starts with the dissolution of the gas in the water, which then presents a greater concentration of carbon dioxide, and this causes the shifting to the right in the chemical balance in the following reaction:

$$CO_2 + CO_3^{--} + H_2O \leftrightarrow 2HCO_3^{-}$$

As a consequence, the oceans experience an increase in the concentration of HCO_3^-, that remains in the superficial water and that is taken in deep water by oceanic circulation only in a temporal scale of 10^2-10^3 years. HCO_3^- is then transformed into shells by sea organisms:

$$Ca^{++} + 2HCO_3^{--} \rightarrow CaCO_3 + H_2CO_3.$$

The climate system has been described as characterized by a great number of subsystems that continuously interact in a non-linear way, and by the presence of feedback mechanisms. Hence, the climate can be defined as a complex system, that is to say it is difficult to explain its dynamics only in terms of those of its subsystems; also, the future behavior of the climate system is impossible to predict exactly, and climatologists design

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[3] According to the IPCC, climate feedback is *"an interaction in which a perturbation in one climate quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first"* (IPCC, 2014).

models – strongly different from the traditional mathematical models of classical physics – aiming at improving the reliability of predictions.

1.3 Climate models

In classical physics, mathematical models of phenomena are equations that describe the relations among different physical quantities involved in the phenomenon analyzed, and that can be analytically solved to predict the evolution of a variable, once the initial conditions are given. In general, classical mathematical models describing physical phenomena can be validated through experiments in laboratory.

On the contrary, when studying the climate, the complexity of the system makes it extremely difficult to create a model that correctly describes its dynamics. Also, to design experiments aiming at the validation or confutation of a certain climate model is impossible, since too many subsystems and mechanisms should be considered and reproduced in a controlled environment as the real laboratory.

As a consequence, meteorology and climatology have long been exclusively observative disciplines (Pasini, 2003): non-linear differential equations were used to describe the behavior of single subsystems but could not be analytically solved. In the second half of the XX century, things started to change because computers could be exploited to solve non-linear differential equations numerically.

Since climate dynamical models are adaptions on longer time scales of meteorological ones, a brief description of the latter is necessary.

Meteorological models are based on combinations of the equations describing the dynamics of the single elements comprising the atmosphere, while the boundary conditions are considered to be constant: in fact, the atmosphere interacts with other systems that evolve slower.

The validation of a meteorological model is not made through a classical experiment, but through a computer simulation. To simulate the complex behavior of the atmosphere is computationally possible only through discretization of the representation; the common space resolution is 30 km horizontally and 100 m vertically (Pasini, 2003).

A problem that arises from the discretization of a meteorological model is that some important phenomena occur in a space scale that is minor than the common space resolution: for example, some storm clouds are smaller than the common cell in the tridimensional space grid, but their role in influencing the meteorological prediction is not negligible. In order to solve the problem just described, the influence of phenomena characterized by short space scale is analyzed and inserted in the model in the form of parameters.

Meteorological models are characterized by a maximum distance in time in which predictions can be considered to be reliable, that is their *prediction horizon*. As a matter of fact, the atmosphere and the climate are complex systems which are characterized by deterministic chaos, that is to say initial conditions that are very close will most likely result in strongly different behaviors. Consequently, errors in the definition of initial conditions in a meteorological model will result in much greater errors in the predictions after a certain period of time, thus it is vital to evaluate the prediction horizon. The latter is commonly set between 7 and 10 days, and its value is evaluated through the method of *ensemble integrations*: the meteorological simulation is made run many times – each time with a different perturbation on the same initial condition – and the prediction horizon is consequently the time after which the different simulations start diverging.

The graph in Figure 1.3 represents different simulations run in order to predict the speed of the wind: it is shown that after 72 hours the prediction cannot be considered to be reliable because the different trajectories diverge.

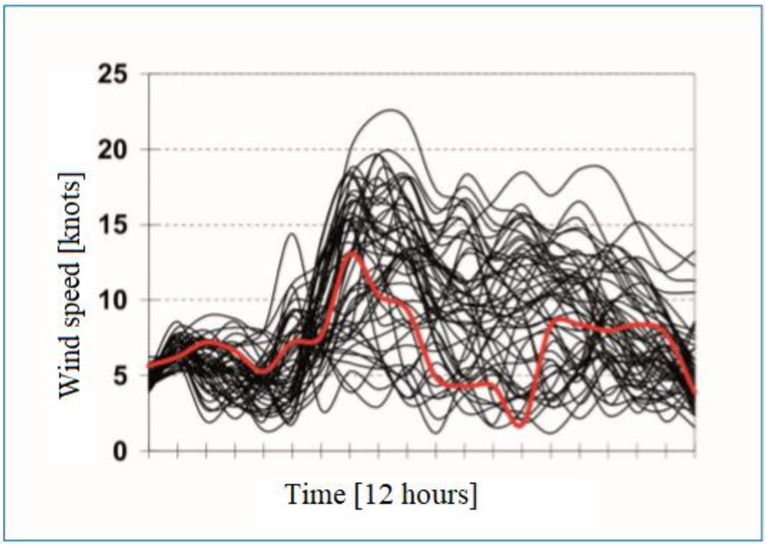

Figure 1.3: ensemble integrations on the speed of the wind. The red line represents the prediction obtained stating with the best estimate of the initial conditions, while the black ones represent predictions obtained with the same model starting with perturbations on the same initial conditions (Pasini, 2007a)

Climate models are based on the rules governing the meteorological ones: a common question is whether it is possible to make predictions on the evolution of the climate, considering the prediction horizon for the meteorological models is 10 days maximum, while climate is to be evaluated on a much longer time scale.

The main difference between meteorological and climate models is that in the latter ones the boundary conditions cannot be considered constant: as a matter of fact, in the time scale in which the climate is studied, the variations in the climate subsystems interacting with the atmosphere are not negligible, and actually strongly influence atmospheric phenomena and are in turn influenced by those. In Global Climate Models (GCMs), the relations between different subsystems are expressed as coupled equations that allow the description of feedback mechanisms.

A method used to simplify the study of the climate is the analysis of periods of time – e.g. the same season in different years – in which the natural boundary conditions can be approximated as constant, that is to say periods of time in which the climate can be considered to be an autonomous system. Autonomous systems are those which trajectories in the state-space converge onto an attractor, that is a locus in the state-space which analysis allows the study of the statistics of the system's dynamics.

When a certain climate model gets validated, that is to say if it correctly represents the actual climate data collected, it can be used to make predictions on future climate: since different climate models are all characterized by a certain amount of errors on the initial conditions and consequently on the evolution of the simulation, multiple simulations are run.

GCMs are also used to validate hypothesis on the causes of the recent global warming: the data representing the latter can be reproduced by simulations only if both natural and anthropogenic forcing is included, as it is shown in Figure 1.4.

GCMs actually simplify the relations and mechanisms characterizing the climate system: the description is not univocal, because the presence of hidden mechanisms and the complexity of the system make it necessary to introduce ad-hoc parameters in order to reproduce correctly the data collected through direct measurements.

Another kind of climate models – data-based models – have recently been developed exploiting methodologies coming from the field of artificial intelligence, i.e. neural networks. These are based on the observation of the fact that the climate system is characterized by climate variables that respond in a certain way to external forcing even after many different feedback loops (Pasini, 2007b). It is thus possible to evaluate the different responses of the climate to external forcing even without analyzing the dynamics of the internal structure: neural networks allow to find non-linear relations between a given external forcing and the following behavior of climate variables.

Neural network climate models are exploited in the process of identification of the causes of the recent global warming, as well as GCMs.

Also, data-based climate models can be used in synergy with GCMs to improve predictions on future climate through the process of downscaling: neural networks are able to determine non-linear relations describing the local response of climate variables to the global change of others.

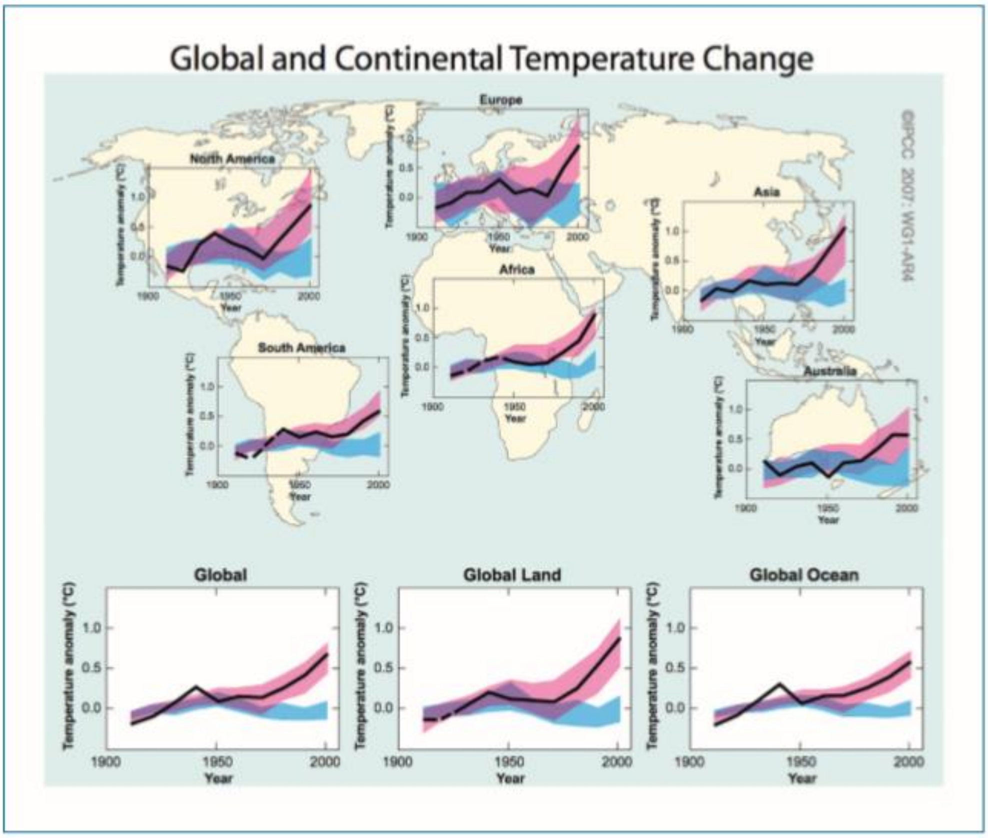

Figure 1.4: validation and analysis of causality by means of ensemble integrations. Black lines represent the observed variability of temperature over the last century; the pink bands represent the results of models that include only natural forcing, while the blue bands represent the results of models that include also anthropogenic forcing. It is shown that natural forcing alone cannot explain the measured variability of temperature (Pasini, 2007a)

A model is an approximated representation of a real phenomenon, since the knowledge of the mechanisms governing the latter – mainly in the case of the climate, and of complex systems in general – is not complete.

Both GCMs and data-based climate models are limited in the description of the climate system but can be used in synergy to make predictions on future climate changes and on the impact of the latter on natural and human systems.

GCMs are designed through the decomposition of the climate system into its numerous subsystems and by focusing on the behavior of the latter and on the relations among them. However, GCMs are limited by the lack of complete knowledge of the totality of the numerous interactions among climate subsystems, and of feedback mechanisms. The limits of GCMs thus arise from the fact that the climate is a complex system.

In order to overcome the limits of GCMs, data-based climate models have been designed and allow predictions on the future behavior of the climate without the necessity to have knowledge of the system's structure. However, data-based climate models are limited by the fact that unprecedented events can cause changes in the climate that could not be predicted in any way. Thus, also in the case of data-based climate models, limitations arise from the fact that the climate is a complex system.

It is then evident that both to describe the mechanisms governing the behavior of the climate system, and to explain how climate models can be used to make predictions on future climate change, it is necessary to help people understand what complex systems are.

Chapter 2
Science of complex systems and educational research

In this chapter, we address the main conceptual issues raised from the science of complex systems and the role and feasibility of complexity education. In the first section, we provide an outline of the general features of complex systems, giving some simple examples of the latter; in the second section, we focus on the difficulties – highlighted by educational research – encountered by novices when dealing with complexity, but we also describe some didactical tools through which it is possible to convey knowledge of complexity; finally in the third section, we focus on role-games and on the power of the latter in successfully providing knowledge about concepts related to complex systems.

2.1 An introduction to complex systems

The reasons for defining a certain system as complex are that there exist some difficulties in describing its behavior, in describing its structure, and in identifying the causes of its dynamics.

Complexity in describing the structure is due to the fact that the latter emerges from the intertwined interconnections among the elements comprising the system, which as a consequence displays a quite surprising behavior that cannot be explained in terms of the behavior of its individual parts.

Even though there is no scientific agreement on a definition of complexity (Ladyman and Lambert, 2013), it is possible to generally describe complex systems by analyzing their common features.

The first necessary characteristic of a complex system is the numerosity of the elements comprising it: while the behavior of a simple, classical system can be accurately described by means of a system of differential equations, conventional tools of analysis become impractical when the number of elements of the system increases.

The elements of a complex system not only are numerous, but also similar in nature, as this is a prerequisite for exchanging energy, matter, or information, thus having the possibility to interact by means of forces, collisions, or communication in general. As a consequence of the numerosity of the elements comprising a complex system, the interaction among them is *"fairly rich"* (Cilliers, 1998), that is to say each element exerts influence on, and is in turn influenced by, a few other ones.

Even if direct communication – i.e. exchange of matter, energy, or information in general – occurs only between neighboring elements, in fact the behavior of one exerts influence on many others that are not directly connected to it. The possibility for wide-range influence to occur, results in the modulation of signals within the structure of the system, that is to say the influence one element exerts on another can be *"enhanced, suppressed or altered in a number of ways"* (Cilliers, 1998). As a matter of fact, similar elements – which we thus assume to react in the same way when receiving the same input – could receive different information because of interactions of different nature, and of a different number of interactions, and thus communicate different responses to their neighbors. Also, elements diverse in nature – which we thus assume to respond differently to the same input – make a message coming from a common neighbor differentiate and get modulated along the way. It is then evident that the macroscopic behavior of the system when responding to a certain input, is not easy to predict.

Another important consequence of the richness of the interaction is recurrency, that is the presence of feedback loops: the way an element interacts with the others influences the way those will interact with it at a later time. An useful tool for visualizing feedback mechanisms are causal graphs (Ladyman and Lambert, 2013), which can be construed by drawing an arrow from an element A of the system to an element B, if A exerts influence on B: feedback is then indicated by a graph with loops of causal arrows, but not by a chain of causal arrows.

Feedback can be either positive – enhancing, if the response to a certain action reinforces the latter – or negative – inhibiting, if the response to a certain input makes the latter diminish in power. Negative feedback leads the system to stabilize, while positive loops determine an acceleration in the response given by the system to a certain input coming from the external environment.

An example of positive feedback in the climate system is the ice-albedo feedback mechanism: the process of ice melting due to global warming results in a reduction of the albedo, thus in more solar radiation absorbed by the system and a further warming. The result is a fast feedback loop. On the contrary, blackbody radiation is a negative feedback mechanism, since global warming causes the increase of the emission of infrared radiation by the Earth’s surface according to the Stefan-Boltzmann law, and this would result in a reduction of the temperature of the Earth, if other feedback mechanisms were not present.

Both the presence of feedback and the intertwined network of relations among the elements make the complex system respond to change in the external environment in a non-linear manner, i.e. the effects are not proportional to their causes. Most of the systems analyzed through the traditional mathematical tools of physics are linear, and a typical example is the simple pendulum, which dynamics can be described – in case the angle θ that the pendulum swings away from vertical is small – by means of the equation

$$F = m \cdot g \cdot \theta$$

where *F* is the force which the pendulum is subjected to, and is thus proportional to the angle θ that describes the perturbation from the equilibrium. The behavior of the pendulum is predictable once the mass m and the initial conditions are known. On the contrary, a double pendulum – a pendulum simply attached to the end of another one – is a non-linear system and cannot be described in terms of the behavior of its elements – the two individual pendula – taken as independent: its dynamics is not predictable and is strongly sensitive to initial conditions. The behavior of the double pendulum is said to be characterized by deterministic chaos, i.e. it is not possible to predict its evolution even though the rules governing its dynamics are deterministic. Chaotic systems are in fact predictable for a while, and then appear to be random.

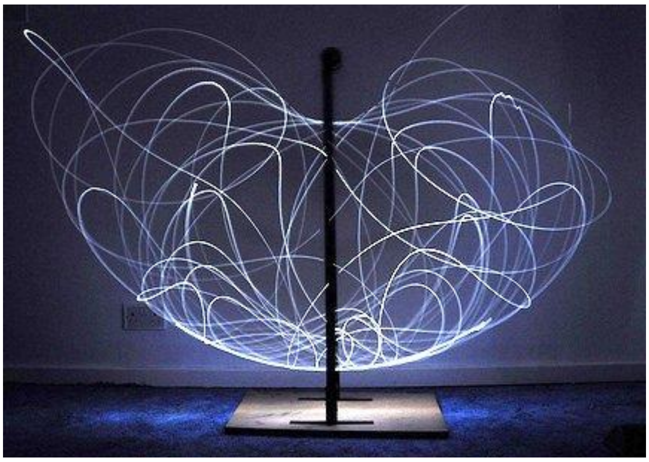

Figure 2.1: trajectory of the mass attached at the extremity of a double pendulum (Amaldi, 2011)

However, the trajectories representing the evolution of chaotic systems in their state-space converge into a finite area of the latter, that is named "attractor": deterministic chaos allow only certain configurations for chaotic systems, which as a consequence cannot be considered random. In Figure 2.1 it is shown the trajectory of a double pendulum. If we run the experiment for multiple times, the trajectories will be different every time but we could notice the possible configurations are always contained in a finite volume. This object – that has finite volume and regular shape for every possible experiment with this physical system – is called the attractor of the double pendulum.

Moreover, non-linear systems *"have typically several solutions"* (Heylighen, 2001), that is to say they are characterized by a number of stable configurations in which they may settle, and the choice of a particular solution depends on the crossing of specific thresholds – "tipping points" – for a certain variable describing their state, and on random fluctuations of the latter that would effectively result in the crossing of the threshold. An example to make this fact clear is the case of magnetization, i.e. the process through which a potentially magnetic material actually becomes a magnet: in Figure 2.2 it is shown the difference between the internal structure of a material before and after magnetization.

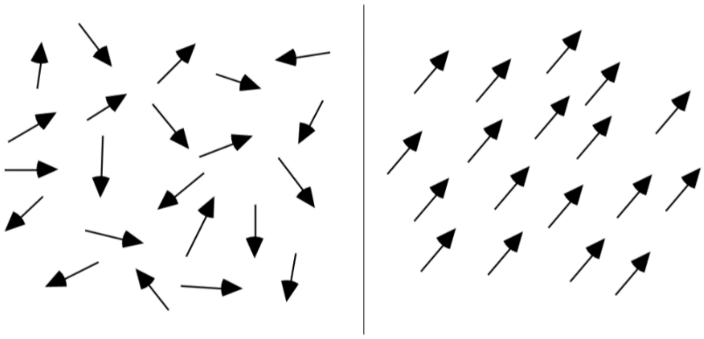

Figure 2.2: two arrangements of spins: disordered (left) and ordered (right). (Heylighen, 2001)

Initially, the material is not magnetic, that is to say the tiny magnets in its internal structure – "spins" – are not aligned one to the other because of the high thermal energy of the molecules. By reducing the temperature of the material, it becomes progressively more probable for the spins to align and thus for the material to become a magnet. The emergence of a macroscopic feature of the system – such as magnetization – is due to self-organization, that is the *"appearance of structure or pattern without an external agent imposing it"* (Heylighen, 2001): the material became a magnet without the intervention of any external designer or internal central control.

The decrease in temperature is not enough for the phenomenon of magnetization to occur, in fact randomness and chance are necessary: it is by chance that one certain spin has aligned to another and this particular configuration has resulted in the creation of a very weak internal magnetic field, which then made other spins align to the first ones. It is thus by random fluctuations – random changes in the direction of the spins – that a initially weak internal magnetic field has caused the alignment of all the other spins, actually allowing the crossing of the threshold of the minimum intensity of the internal magnetic field necessary for making the material become a magnet.

Self-organization occurs only in distributed organized systems, in which each element contributes to the resulting configuration and macroscopic behavior: *"in practice, different alignments will appear independently in different parts of the material, and compete for the recruitment of the remaining non-aligned spins. That competition is usually won by the assembly that has grown largest"* (Heylighen, 2001).

The property of self-organization can be brought to the fore also through the description of the Bénard phenomenon, which is an example of a system that *"produces a stationary state of on-going activity"* (Heylighen, 2001) – differently to the case of magnetization, in which the system reached equilibrium, i.e. it displayed a static pattern.

Bénard phenomenon emerges when a liquid is heated from below and is in contact with a cooler environment at its surface: convection takes place in the liquid, as it is determined by the individual behaviors of different portions of the liquid. As a matter of fact, portions in contact with the hot surface at the bottom will try to move upwards while the cooler portions of liquid will try to sink from the upper surface towards the bottom. Thus, Bénard rolls emerge from an attempt to find coordination between the two flows of liquid: self-organization is the emergence of global organization through local interaction, without any central control or external designer. Figure 2.3 represents the difference between a disordered movement of molecules in a liquid, and the pattern emerging in the phenomenon of Bénard rolls.

In this latter case as well, it is possible to see that an initially disordered system settles in a stable configuration – which could not be predetermined – when a certain threshold is crossed: Bénard rolls will only appear if the difference in temperature between the bottom and the upper surface is large enough, while if it is not heat will be exchanged by means of mere diffusion and the phenomenon will not emerge.

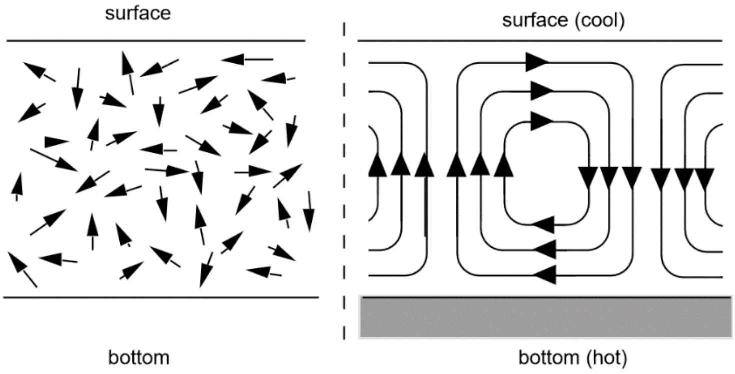

Figure 2.3: two different types of movement of liquid molecules: random (left) and in the form of Bénard rolls (right). (Heylighen, 2001)

What has just been stated can be represented through a bifurcation graph, as it is shown in Figure 2.4: if the difference in temperature is not great enough, the movement of molecules in the liquid is disordered and their average speed is null, while once the threshold is crossed two different configurations are possible, that are the Bénard rolls moving either clockwise or counterclockwise.

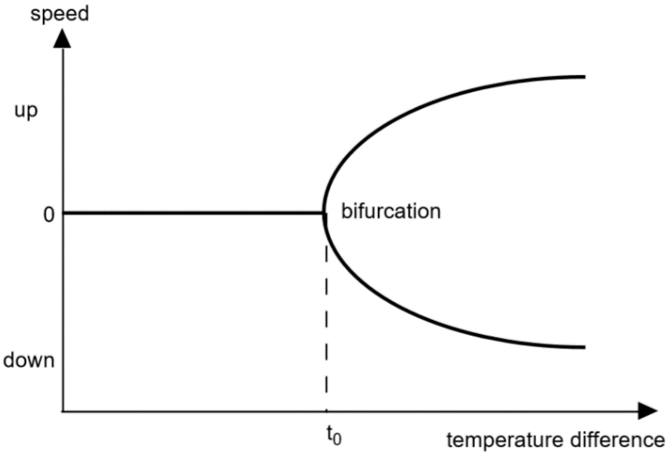

Figure 2.4: the bifurcation characterizing the appearance of Bénard rolls. When the temperature difference increases – at time t_0 – two different outcomes are possible for the average speed of the molecules: the latter can move either upwards or downwards (Heylighen, 2001)

The choice between the two different configurations is driven by chance fluctuations, that is to say it is by chance that a group of neighboring molecules start to move clockwise or counterclockwise, and as a result influence the other molecules of the liquid to move in a certain direction.

Bifurcation graphs can be extremely more complicated, *"instead of two, there can be three, four or any number of solutions appearing at a bifurcation point, and bifurcation may be arranged in a "cascade", where each branch of the fork itself bifurcates further and further"* (Heylighen, 2001).

The settlement into an ordered configuration from a disordered initial one, that is how a complex system displays self-organization, can prove to be very counter-intuitive: most of the systems analyzed by traditional physics increase their disorder when left to themselves. In order to reconcile self-organization with traditional physics, it is necessary to indicate a further characteristic of complex systems, that is they are open systems, thus the excess of entropy that is continuously generated gets dissipated to the external environment.

The term "organization" not only refers to the fact that the internal structure of a complex system is ordered, i.e. it displays a well distinguishable pattern, but also to the fact that the structure is aimed at fulfilling a particular function, which is the *"maintenance of a particular configuration, in spite of disturbances"* (Heylighen, 2001). A self-organizing system displays the ability to adapt, to modify its structure in order to cope with changes in the external environment. The emergence of a structure through self-organization is already a kind of adaption to the environment because it follows from the response each element of the system gives to external inputs. However, adaptive systems are those that can adjust to changes in the boundary conditions while maintaining their organization. When a magnet is put in a strong enough magnetic field, which direction is different to the internal one's, the spins on the outer fringe of the magnet will be the first ones to adapt, since the internal magnetic field they are subjected to is the weakest. The more interior layers of spins will consequently adapt to the first spins that have changed their orientation, and the final result will be the switch in the orientation of the magnetic field created internally. Adaption is therefore possible through local interaction and lack of central control.

In order to explain how the ability of the system to adapt to its environment and to cope with any change that may occur, it is necessary to assume the system is able to learn and remember what has been learnt of the behavior of the environment. A complex system needs to store information on previously encountered situations. The system remembers and forgets in the sense that the repetition of a certain input from the outside will result in a certain pattern due to the structure of the system, because of the ensemble of answers from the single units. If an input from the external environment does not keep happening, the structure will respond to that single input but then adapt to the new inputs and thus forget the previous one.

A model that can help to understand the property of self-organization and memory of complex systems is the neural network: each element of the system is represented by a node which is connected to others through synapses, that are characterized by different strengths or weights according to how much they are actually used. Also, in the neural network model, the exchange of information between the system and the environment is possible through sensors that can sense aspects of the environment, and that are connected to the single units of the system.

Another important feature of complex systems is path dependency, that is to say the precise historical path taken by the system is of crucial importance for the future behavior of it.

2.2 Teaching complexity

Concepts associated with the study of complex systems appear to be counter-intuitive, in the sense that they contrast with the more commonly held beliefs: people are used to explaining any kind of phenomena through linear thinking, centralized control, determinism, and reductionism, while they commonly refuse randomness as a stimulus for the emergence of an ordered pattern (Jacobson & Wilensky, 2006).

As Jacobson stated in a study on the different approaches to problems adopted by experts and novices in the field of complex systems (Jacobson, 2000), not only there are differences in the concepts known by the two groups, but also in the epistemological and ontological beliefs about the world. Novices in the field of complex systems adopt a reductive and deterministic approach, they search for a single cause for the behavior of the system, which they consider to be linear, and for a function of the system. On the contrary, experts in the field of complex systems analyze a system considering the relationships among the elements and describing the dynamics in terms of equilibration processes. When it comes to explaining the behavior of a complex system, novices often what Wilensky and Resnick call a "deterministic-centralized mindset". Indeed, novices of all ages tend to see a complex system as a deterministic "clockwork" system, where the elements are interconnected like gears in clockwork. Moreover, they usually think that the emerging patterns have to be explained only with a centralized leadership (Wilensky & Resnick, 1999).

Even though systems-oriented education is important for appreciating the world as presenting interlocked complex phenomena and how those are dependent to many factors and can display unexpected behaviors, complexity is rarely taught at school because of the belief a high level mathematical training is necessary.

In fact, scientists that investigate in the field of complex systems often describe the behavior of the latter by means of systems of non-linear differential equations. Also, statistical methods are necessary for the study of the dynamics of complex systems, since order at the macroscopic level emerges from a structure characterized by some form of randomness; yet, it has been documented that learners encounter difficulties in grasping the meaning of statistics (Wilensky, 1996), and this fact represents a limit to the understanding of complexity: difficulties are encountered in the comprehension of how can something be both random and structured. In school, statistics is taught simply as an assemblage of formulae, thus learners often do not understand what they are doing (Wilensky, 1996).

However, it has been claimed that students can actually understand some concepts concerning complexity, and can build a systemic mindset even without a high level mathematical training. As a matter of fact, in a study conducted by Richard Plate (Plate, 2010), it is pointed out that, while conventional education does not provide students with the necessary tools for understanding complexity even at a high level of education, systems-oriented instruction can help learners even in middle school to interpret complex social and ecological systems through non-linear mapping of causes and consequences. It has also been documented that complex systems' concepts, such as circular causation, can be taught to children in elementary school (Roberts, 1978). Complexity has not only been addressed at school levels, in formal, informal and non-formal contexts, but also with adult citizens. In the study described in (Barelli, Branchetti, Tasquier, Albertazzi & Levrini, 2018) many adult citizens, with disparate jobs, educational backgrounds and levels of interest on science, were involved in a project aimed to explore crucial issues of science of complex systems as the basis for the development of citizenship skills.

In order to make systems-oriented education effective, not only complex systems are to be described, but also new explanatory frameworks and educational methodologies are demanded. Students encounter difficulties in understanding complex systems if lessons are focused only on the conceptual level, because a change in the causal reasoning is demanded. As a matter of fact, Jacobson suggested that *"helping students understand and use complex systems knowledge will require attention to issues of conceptual change and to helping students construct a richer conceptual ecology which embraces both non-reductive and decentralized thinking, multiple causality, non-linearity, randomness, and so on"* (Jacobson, 2000).

In addition, Wilensky and Resnick suggested that learners can better understand complex phenomena when connections are made between different levels of the system (Wilensky & Resnick, 1999). As a matter of fact, distinguishing the macroscopic level and the microscopic one – and indicating the causal relationship between the two – is important to help students understand the necessity of abandoning the reductive and linear approach and thus interpreting the macroscopic behavior in terms of the dynamics of the elements at the microscopic level.

When describing the hierarchical structure of complex systems, it is necessary to consider the typical misconceptions linked to the concept of levels. Wilensky and Resnick indicated three different interpretations of the concept of levels, two being wrong and misleading when the field of complex systems is concerned.

The *"organization-chart view"* (Wilensky & Resnick, 1999) is based on the idea that a higher level has control on the lower ones, and is rooted in the culture at general because it is typical of many social organizations, e.g. the army. In fact, this view is misleading because in complex systems the macroscopic level displays a certain behavior because of what happens at the lower levels.

The second possible way to interpret the hierarchical structure of complex systems is the *"container view"* (Wilensky & Resnick, 1999), that is to say a lower level is viewed as part of the higher one just as a minute is a part of an hour, thus the whole is considered only as the sum of the parts. This view of the hierarchical structure is misleading because the behavior of the macroscopic level can be explained only abandoning the reductive approach.

Finally, in the *"emergent view"* (Wilensky & Resnick, 1999) a higher level is composed of the parts at the lower one, and its behavior emerges from the relationships among the parts.

In order to help learners to understand emergence, researchers in the field have designed many didactical tools that focus on the microscopic level of complex systems. For example, StarLogo is an agent-based modeling program, using which students can explore systems with multiple interacting objects: users can program the behavior of each agent, and the way it interacts with the others and with the environment. The latter is computationally active as well, that is to say its behavior is programmable by the users of StarLogo, and can keep trace of the movement and behavior of the agents. Using StarLogo, learners have the possibility to see how the macroscopic behavior of the system emerges from the rules they put for the microscopic level agents. Another example of an agent-based modeling program that can be exploited to help learners understand emergence and complex systems, is NetLogo – an expanded version of StarLogo – that was designed in order to make the language easier to use and more powerful.

A possible critique to computer-based modeling activities like StarLogo and NetLogo, is the fact that no real phenomena can be described. This can lead to resistances in novices who do not understand the strong role of scientific modelling behind these simulations and reject these tools as instruments able to capture some aspects of real phenomena. This aspect becomes particularly evident when simulations of complex social phenomena are addressed (Barelli, Branchetti & Ravaioli, 2019).

However, it has been documented that learners encounter more difficulties in understanding complexity when lessons are focused only on the conceptual level, that is to say on the simple description of a number of complex systems and the listing of their common features. From the point of view of constructionism, the necessary shift from the traditional to the systemic mindset is possible only after having had experience of a complex system: cognitive growth is possible only through *"a dance between diving-in and stepping-out"* (Ackermann, 1996). However, it is not possible to reproduce a complex system in a traditional scholastic laboratory, thus it is necessary to provide students with another educational tool that give them the possibility to make sense of the microscopic mechanisms that give rise to emergent properties.

Once the new mindset is forged, students are ready to analyze different real complex systems applying the concepts they have learnt.

2.3 Role-playing activities for teaching complexity

Another educational methodology that makes it possible to focus on the microlevel of the system and on the relations, which are the actual cause of the emergent behavior, is the development of role-playing activities. *“Role-play is a product of ‘play’, ‘games’ and ‘simulations’”* (McSharry & Jones, 2000) and seven categories of role-playing activities can be indicated, of which *“analogy role-play”* – activities in which participants represent elements of a system or of scientific theory – *“can be used to teach the more difficult scientific concepts – those which, for reasons of size or logistics, cannot be demonstrated easily in the laboratory”* (ibidem).

Role-games are rare in science classrooms, nevertheless the field of complex systems is particularly well-suited for this kind of activities: the microscopic relations – that are the actual cause for the macroscopic behavior of a complex system – are represented by interaction among participants, thus a learner can – by acting out the role of an element within a complex system – appreciate the confinement of control, the locality of interaction, and the arise of macroscopic pattern.

An educational game on complexity should be a complex system itself (Van Bilsen, Bekebrede, & Mayer, 2010): a high number of participants is demanded in order to develop a rich interconnection and to have multiple possible outcomes. For this reason, role-playing activities aiming at teaching complexity should be proposed either to a large audience in an extra-scholastic environment, or at school to two or three classes together. Through a debrief following the game, many features of complex systems – such as interdependencies, feedback, non-linear evolutions – can be easily brought to the fore. First of all, the emergence of a macroscopic pattern from the microscopic interactions is evident, as well as the absence of central control since each participant has a limited view on other interactions and on the behavior of the system as a whole. Also, discussion on the game can help participants understand the concept of path dependency, that is the dependence of the system’s behavior on its previous history: as a matter of fact, the historic progression influences the remaining duration of the game.

Chapter 3
Teaching complexity through games

In this chapter, we aim to design a draft of teaching path to describe some important features of complex systems. In order to make the understanding of complexity accessible to everyone, what we propose here are four role-playing activities that do not require a high level of mathematical training to be carried out and understood.

The activities were adapted from those proposed in the book "The systems thinking playbook" by Linda Booth Sweeney and Dennis Meadows, and in the article "Diving into complexity: developing probabilistic decentralized thinking through role-playing activities" by Mitchell Resnick and Uri Wilensky. After having explored the existing materials on role-playing activities, we have selected four activities that we considered crucial to introduce the main ideas of complex systems. The original character of this work consisted in carrying out a detailed analysis of the activities to highlight where and how the concepts of complexity could be traced in the games, and to suggest possible attention points to consider when introducing these activities to an audience of novices.

In the followings, we will summarize the main features of each activity, and their roles in the teaching path.

The first activity is called *"Triangles"* and is composed of two independent parts. The first one is original and was designed taking the cue from a game developed in the program "I SEE" (https://www.youtube.com/watch?v=vPVbdV3FQoI), while the second part is a modified version of an activity described in (Sweeney & Meadows, 2010).

"Triangles" is the starting activity of the teaching path because it focuses on one of the most peculiar characteristics of complex systems, that is the emergence of behavior resulting from the intertwined internal structure of the system and feedback mechanisms. Through this game, the concept of attractor is introduced.

The second activity is called *"Living Loops"* and it was adapted from (Sweeney & Meadows, 2010). It was chosen as the second activity because it focuses on feedback mechanisms, that have been already introduced in *"Triangles"*.

The third activity is *“Segregation”*, based on a role-playing activity described in (Resnick & Wilensky, 1999). It focuses on the concept of attractor, that was previously introduced in the teaching path, and on tipping points.

“Harvest” is the last activity, and it was built based both on the one described in (Sweeney & Meadows, 2010) and on the activity presented by Eleonora Barelli in her master’s thesis “Science of complex systems and future-scaffolding skills: a pilot study with secondary school students” (2017). Through this last game, participants have the possibility to put into practice what they have previously learned on complex systems, by adopting a game strategy in order to reach the preferable configuration for the system.

The description of the rules of each game we propose is followed by a brief comment on how the activity can facilitate the understanding of the science of complexity.

3.1 “Triangles”

This activity is composed of two parts, that are not connected but that are organized in one activity because of the similarity in the set up – very simple with minimal material necessary – , in the type of interaction among participants – only movement – , and in the large space necessary for the participants to move around.

Description of the activity

Number of participants: more than 20
Duration: 20 minutes
Materials: set of numbered 210x297 mm cards (paper A4), one for each participant. The cards are different in color in order to distinguish participants: card number 2 is red, odd numbered cards are blue, the rest of the cards are white.

In the first part of the activity, participants are led to experience emergence in complex systems.

Rules for the first part of the activity:
Participants walk around freely in the large area selected for the activity.
Each player has to choose another participant from the group.
The game operator asks everybody to keep moving with the only rule to have the person selected in view. Participants know only their own selection.
Each player selects a second person to keep in his/her view while walking.
The game operator then asks players to add other people, one by one, to the ones previously selected to keep in their view, and to continue moving around.
Finally, the game is stopped by the game operator when a circular pattern forms.

In the second part of the activity, the focus is on the absence of central control and on the interaction among different elements of the system. There is no part of the system that is isolated from the others; elements that have many connections have major influence on the whole system.

Rules for the second part of the activity:
Cards are distributed to participants, who display their own on their shirt fronts: each participant has his own number.
The game operator announces that players will have to choose two other people from the group to be their reference, and that this selection will have to be made observing two rules: all odd numbered participants will choose number 2 as one of their references, and no one should select any person whose number is a multiple of 5.
Participants do not know the other people's references.
Each player has to move around in the room so that he/she is equally distant from his/her two references. It will take a few minutes before everyone slowly comes to a stop.
Then, this short activity is repeated in three different situations:

1. Participants whose number is a multiple of 5 are asked not to move, while the others have to start again walking around in the room until they are equally distant from their two references. Everybody will come to a stop in approximately the same time as in the previous situation: as a matter of fact, the people that were asked not to move are the ones that were not chosen by anyone to be a reference, thus they do not exert influence on others in the group.

2. The game operator chooses five participants whose number is neither 2 nor a multiple of 5, and asks them not to move, while all the other people have to start again walking around in the room until they are equally distant from their two references. In this situation, the group will take less time to come to a stop than in the previous one, because the people asked not to move exert influence on other participants.
3. Participant number 2 is now asked not to move, while all the other people have to start again walking around in the room until they are equally distant from their two references. In this last situation, the group will come to a stop very quickly, because participant number 2 exerts influence on half of the people.

Analysis of the activity

"Triangles" helps to highlight some features of complex systems, that are self-organization, non-linearity of interaction, and emergence. In particular, the first part of the activity is mainly useful for discussing emergence and the concept of attractor. The second part of the activity can be a starting point for describing self-organization.

Emergence is a consequence of non-linearity in the interaction among elements of the system and of self-organization, and results in a surprising behavior displayed by the system as a whole. The circular pattern that emerges from adding more interactions can be easily described macroscopically, but the cause of it is quite hidden and cannot be explained by considering only the dynamics of the parts.

Another important concept that can be brought to the fore through this activity is that of attractor. In the science of complexity, the behavior of a system can be studied by means of representation of the state of the elements in state-space, and of the possible trajectories, which converge to a certain area of the state-space which is called attractor. Any change in the initial conditions will not modify the nature of the interactions among the elements of the system, and as a result the circular pattern will emerge anyway.

Both the first and the second part of the activity show the complexity in the internal structure of the system, thus can help describing the concept of self-organization. In fact, the structure of the system defined by the rules given in the two parts of the activity results to be quite simple, while in a real complex system the interaction can be much richer and more complicated. However, it is still possible to show participants that the behavior of one element of the system can influence others both directly and indirectly. As a matter of fact, the movement of one person can influence the movement of another if the first one has been chosen as a reference by the second one; also, the movement of the second will influence the movement of other people who have chosen that person as a reference, thus the behavior of the first person indirectly influences many others.

Features of the structure of complex systems that are not described in the activity are the fact that elements of the system can be substituted and their number can change, and the fact that the emergent behavior of the system as a whole is influenced by the external environment as well.

It can be useful to start the debrief on this activity by asking to participants if they would have expected the behavior of the system to occur as it actually did: this question can be asked also before the beginning of the activity, in order to start the debrief by comparing the actual behavior of a complex system to common expectations.

During the debrief, the game operator could ask participants whether they consider the numerosity of the elements of the system to be a sufficient condition for emergence. In fact, numerosity is only a necessary condition, while a *conditio-sine-qua-non* for emergence is non-linearity of the interaction: in order to make this fact clear, during the debrief the starting point of the first part of the activity can be proposed again to participants. Making people walk around in the room and asking them to choose only one other person in the group to keep in their view, is a situation in which the system is characterized by numerosity of the parts and the interaction among those is quite simple: the circular pattern consequently will not emerge.

During the debrief of this activity, the concept of attractor can be described, even though a representation in the state-space is not possible. In order to do that, the first part of the activity is repeated asking participants to choose people as references that are different from the ones they have chosen the first time, thus changing the initial conditions. The circular pattern will emerge again, even if participants will be in the circle in a different order. The important role of randomness can also be brought to the fore, and thus the impossibility to determine the behavior of the system with certainty, because of the impossibility to know who the participants will choose as their references.

In order to highlight the fact that emergent behavior results from a complex structure, during the debrief on the activity it can be useful to create a causal graph on a blackboard:

names of participants are written randomly on the board, and each person is asked to draw an arrow connecting his/her references to his/her name. In this way, all the influences will be evident.

In the second part of the activity, the focus is also on the fact that some elements composing the structure have major leverage (number 2) or null leverage (numbers that are multiples of 5). In fact, in real systems it is not possible to find elements that do not exert influence on others because their dynamics would for sure influence at least another element; still, in the activity, it is useful to highlight different levels of influence an element can exert on others, thus also null leverage interaction is considered.

3.2 “Living Loops”

This activity helps participants understand the kinds of behaviors that positive/reinforcing and negative/balancing loops can create.

Description of the activity

Number of participants: 10 or more

Duration: 20 minutes

Materials: one 210x297 mm (paper A4) card per player that has a large “+” sign on one side and a large “-“ sign on the other; a piece of string per player: participants can slip the loop of string over their heads and display the card on the front of their torsos.

Rules:

The players stand in a circle, shoulder to shoulder, and display their card on the front of their torsos. The game operator participates in the activity as well, so he/she joins the other players in the circle.

Participants clench their left hand into a fist and hold it out at waist height, while their right hand rests lightly on the fist of the person to their right.

The game operator explains that right hands are “passive”, in the sense that participants cannot move them voluntarily but only as a consequence of the movement of the left fist of the person to their right.

Left hands are “active”, in the sense that participants move them voluntarily, in response to the movement of their right hands: players who are wearing a “+” sign must raise their left hand a few centimeters if their right one has moved upwards, on the contrary they have to lower their left hand a few centimeters if their right one has moved downwards. Participants who are wearing a “–” sign must move their left hand in the direction opposite to the one in which their right one has moved. Once a hand has been moved, it has to be maintained at the height it has reached.

All participants position their card so that the “+” sign faces out.

The game operator sends a starting “signal” or pulse to the person on his/her left by raising his/her left hand a few centimeters above waist level. All participants are wearing a “+” sign, thus each player will raise his/her left hand a few centimeters every time his/her right hand is moved upwards.

The impulse will move around the circle several times, until a player eventually reaches the limit of his/her ability to reach higher, and the signal will have no option but to stop. The group created a reinforcing loop. All reinforcing structures have limits that determine how far they can grow in one direction.

Then, the game operator asks participants to arrange their hands as in the beginning, holding them out at waist level. The game operator now sends the initial pulse in the opposite direction, by lowering his/her left hand a few centimeters under waist level. Since all participants are still wearing a “+” sign, each player will lower his/her left hand a few centimeters every time his/her right one is moved downwards. Again, a reinforcing loop is created, and the signal moving around the circle will stop as soon as one player reaches the limit of his/her ability to move his/her left hand downwards, by touching the ground.

Now, one player is asked to switch his/her sign from “+” to “–”. Participants arrange their hands as in the beginning, holding them out at waist level. The game operator sends a starting pulse to the person on his/her left by raising his/her left hand a few centimeters above waist level. The signal will move around the circle and its direction gets reversed every time it reaches the person with the “–” sign. As a consequence, the loop will oscillate indefinitely, and the game operator stops the signal after the latter has moved around the circle for 4-5 times.

The game operator asks everyone to arrange their hands in the initial configuration, holding them out at waist level. The starting pulse is now sent downwards by the game operator, and the oscillating loop pattern will show again: in a balancing loop, the direction of the initial signal makes no difference to the system’s behavior, while in a reinforcing loop it does make a difference.

Analysis of the activity

This activity focuses on the mechanism of feedback, even though the concept results here much simplified. In the first situation presented, that is the one in which every participant is wearing a “+” sign, a simple positive feedback mechanism is described, in which the response of each element to the action of his/her neighbor amplifies the behavior of the system as a whole. The behavior is represented by the simple movement of hands and it is exemplified by the level reached by the hands.

Systems characterized by positive feedback are usually unstable and are brought to diverge. In the case presented in the activity, the amplification of the behavior of the system is stopped by the physical limit of participants to reach higher or lower. It is vital to help participants understand that if the signs were all “–”, the feedback would have been positive as well.

When a “–” link is added, that is to say when a person is asked to switch the sign from “+” to “–”, a negative or balancing feedback is created: the responses of the system to the previous signal balance the behavior of the system itself. The systems with balancing feedback are usually stable and convergent. In the example represented in the activity, the signal would have kept oscillating indefinitely. A good example for balancing feedback that can be brought to participants from classical physics is a floating buoy: if the buoy moves downwards, it is pushed up through the increasing buoyant force, while when the buoy moves upwards the buoyant force reduces in intensity and the buoy consequently sinks.

“Living Loops” presents a quite simple example of feedback mechanism. As a matter of fact, only simple systems are characterized by either positive or negative feedback, while the majority of systems - and in particular complex systems, which we aim to describe - display multiple feedback loops. The behavior of a complex system is very complicated to predict because the feedback loops characterizing it frequently contain mixtures of

positive and negative feedback, and these two types of responses actually also interact with each other.

During the debrief on this activity, the game operator can invite participants to design another situation, that is adding a "–" link to the loop: this would create a reinforcing loop again, and could lead to the discussion on the possibility to correct the behavior of the system once the mechanism that controls it is known, cancelling the effect of the behavior of one element of the structure by stimulating the system externally. Once the feedback properties of a certain complex system have been analyzed, an alteration in the behavior of the system can be made in order to meet needs of an application.

The debrief on the activity can be followed by a description of the main feedback processes characterizing the climate system: they cause the amplification or reduction of each climate forcing, the term "forcing" meaning a variation of the external conditions that results in a change of the state of the system.

3.3 "Segregation"

This activity focuses on feedback, on the concept of attractor, and on that of tipping points, and presents the possibility for complex systems to display a behavior characterized by a ripple effect.

Schelling's model of segregation can be described during the debrief.

Description of the activity

Number of participants: more than 20

Duration: 10 minutes

Materials: one 210x297 mm (paper A4) card per player; on half of the cards a circle is drawn, a triangle on the other half, in order to distinguish two groups; a piece of string per player: participants can slip the loop of string over their heads and display the card on the front of their torsos.

Rules:

The cards are distributed randomly to participants.

The game operator asks players to randomly choose a number between 1 and 5, then he arranges them into 5 groups of like-numbered people: the groups are not composed of the same quantity of people because the choice of the number is random. Also, since the distribution of shapes drawn on the cards is not correlated to the numbering, each group is typically composed of different ratios of “triangles” and “circles”.

The game operator announces that the difference in the shape on the cards of participants will affect the interaction among people in each group. Now, it is only the shape displayed on the cards that is important, while the numbers participants have chosen are not relevant anymore.

Then, the game operator announces that there is only one rule for participants to follow: if a group is dominated by one shape (composing at least 2/3 of the group), people in the group that have the other shape must leave the group and join another one. For example, whether in a group there are five triangles and two circles, then the latter have to leave and join a neighboring group. However, if a group has roughly even numbers of triangles and circles, it is stable and no one has to leave. In fact, the stability of one group is only temporary if it is joined by people who have left other groups.

Participants should follow the rule until the system eventually stabilizes.

Analysis of the activity

In the early Seventies, the American economist Thomas Schelling created an agent-based model to explain segregation in society. It was quite a simple model, in which only two racial groups – black and whites – were considered, and individuals of the two groups were the agents in the model; segregation was analyzed as emerging in cities: residential areas were represented by a grid, whose spots were as a consequence houses. In Figure 3.1, the two racial groups are represented by stars and zeros.

The model was based on the hypothesis that each individual of one racial group tolerates a certain number of people of the opposite group in his own neighborhood. If one person is not satisfied with the percentage of people of the opposite racial group in his own neighborhood, he moves until his demands are met. Schelling demonstrated that segregation emerges from simple rules of movement and simple definition of tolerance in terms of ratios of people of the two racial groups in one neighborhood.

It is necessary to define tolerance and neighborhood. Tolerance is defined in terms of percentage of people of the opposite racial group in the neighborhood an individual is in. Given this definition, the percentage can be varied in the model.

A neighborhood is defined in terms of the number of spots close to the one in which the individual is, for example it could be the eight spots adjacent to the one in which the individual is.

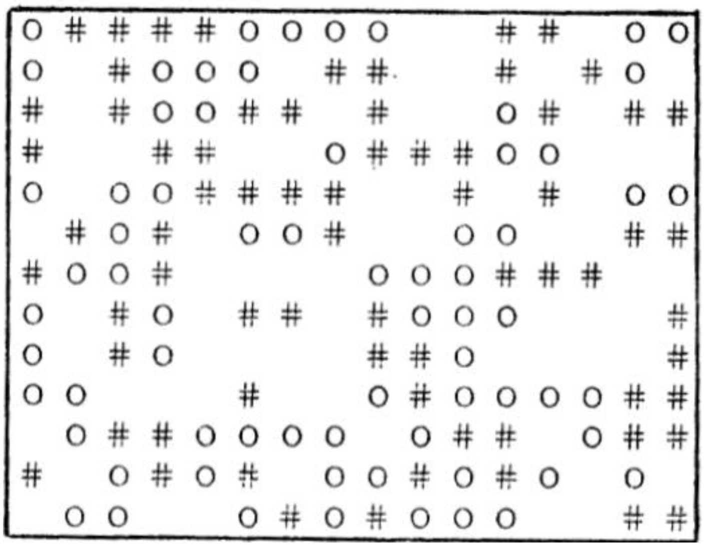

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Figure 3.1: initial random distribution representing the initial random conditions of the segregation model designed by Schelling (Schelling, 1971)

In the grid representing residential areas, some spots are vacant in order to allow movement of individuals from one to another, in particular Schelling found that the best percentage of vacant spots on the total number of spots is between 20 and 30 percent.

For simplicity, the total numbers of individuals of the two racial groups are equal, and each individual has the same percentage of tolerance on his neighbors. The initial distribution of individuals of the two different racial groups and vacant spots are random. Once tolerance is defined in terms of percentage, “satisfaction” of each individual is reached only if the ratio of people of the opposite racial group is minor than tolerance. If an individual is discontent with his own neighborhood, he moves to the nearest vacant spot – *“nearest” measured by the number of squares one traverses horizontally and vertically”* (Schelling, 1971) – in which he will be surrounded with a neighborhood that meets his demands. Since tolerance is defined in terms of percentage, also vacant spots are to be considered in the counting.

Also, a definition of the order in which individuals move is necessary, because the movement of one will influence the movement of others in his neighborhood, and consequently in the grid in general. In fact, the particular outcome will depend on the order of moves, while the character of the outcome will not.

Schelling demonstrated that segregation, that is to say the separation of the two racial groups into two different areas of the grid, emerges from the simple rules that define the model: in Figure 3.2 segregation patterns are displayed. What is surprising about segregation is that the resulting percentage of people of the opposite racial group in one individual's own neighbor is minor than the one defining his tolerance. This surprising fact is due to the ripple effect caused by movement of a single individual, and that comes to a stop only when stability in the segregation is reached.

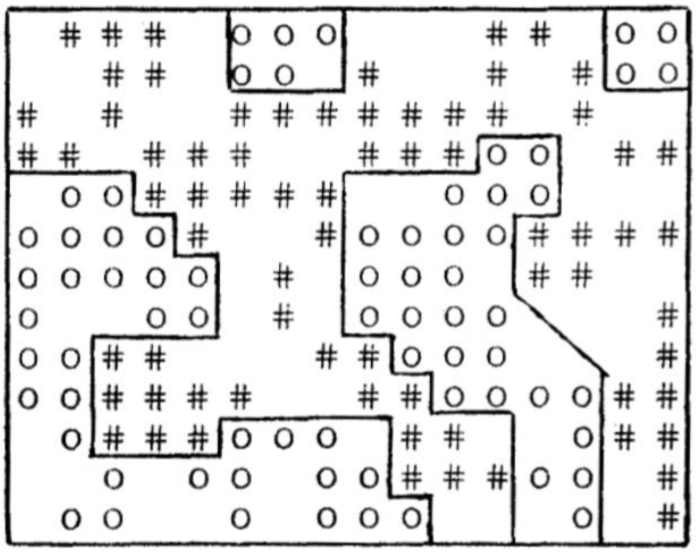

Figure 3.2: segregated patterns emerged by following the rules imposed in the model by Schelling (Schelling, 1971)

Schelling created different variations to the model described above, in order to study how those influence the resulting pattern in the distribution of individuals of the two racial groups: what can be varied is the neighboring size, the tolerance percentage, the ratio of blacks to whites in the total population, the rules governing movement, the percentage of vacant spots.

For example, increasing the demand for like neighbors results in a greater number of people that are initially discontent, and in a final distribution that is characterized by an augmented segregation.

This simple model of segregation created by Schelling is very similar to the situation presented in the activity but differs from the latter in the diverse definition of neighborhood. As a matter of fact, in the activity neighborhoods are not defined in terms of neighboring spots, but space is compartmented and there are no individual positions within the groups defined: a person is either inside a group or outside of it. Since the number of people composing a certain group is not fixed and can change, absolute numbers do not matter, but only ratios.

During the debrief on this activity, the concepts of self-organization, emergence, attractor can be revised; also, Schelling's model of segregation can be described, and the activity can represent a starting point for an analysis of the model by means of computer agent-based models.

However, the main focus of the debrief should be on the concept of tipping points, in order to have the possibility to lead the discussion on tipping points in the climate system. A tipping point is a critical threshold at which a small perturbation causes a rapid change in the state of a system: in the activity, this situation occurs when participants – who have just left their previous group – join a group in sufficient numbers to cause the earlier dominant subgroup to leave.

As it is evident from the three examples reported, tipping points are not independent but crossing a certain threshold could result in a cascade of interrelated irreversible changes.

Another phenomenon influencing the dynamics of complex systems and occurring in the activity proposed is the ripple effect: the movement of one person from a group to another one often results in many other individuals leaving their previous group to join a new one. This phenomenon is a consequence of the complex structure of the system, and is a concurrent cause for the difficulty in the prediction of the resulting state of the system.

3.4 "Harvest"

This activity helps participants better grasp the concept of feedback and brings them to reflect on the so-called "tragedy of the commons" and the need to analyze systems' long-term dynamics.

"When a tragedy of the commons situation kicks in, people who are acting to advance their own well-being cause the collapse of the very environment on which that well-being depends" (Sweeney & Meadows, 2010).

Description of the activity

Number of participants: ideally between 10 and 40, divided into 4 teams
Duration: 30 minutes
Materials: 30 paper figures of fish, 50 coins, a table, one chair per participant

Rules:
Participants are divided into four teams whose goal is to maximize their assets by the end of the game. Teams can sit or stand anywhere in the room, but they should be far enough from one another that no team overhears another's strategy.
The game operator arranges 24 fish on a table, that represents the ocean.
Teams will play for ten "years", and each turn is composed of four parts:

1. Decide how many fish to harvest: during the first turn, each team can get only one fish. In the following ones, each team can choose whether to invest their coins in order to harvest more fish:
   - \$0, the team can get one fish from the "ocean", only if more than 15 fish are still available
   - \$1, the team can get two fish from the "ocean", only if more than 15 fish are still available
   - \$2, the team can get 1 fish
   - \$3, the team can get 2 fish
2. The teams can invest their coins in order to get the priority to the fishing: the game operator processes the orders of fish, either in a random order or starting from the team that have invested more coins.
3. Depending on the total number of fish harvested, each team earn coins:
   - If (number of fish) > 10, each team get \$1 per fish harvested
   - If 7 < (number of fish) < 10, each team get \$2 per fish harvested
   - If (number of fish) < 7, each team get \$3 per fish harvested

4. Fish regeneration: if the number of fish still available in the ocean is F, the game operator adds F/3 fish to the ocean

Analysis of the activity

Through this activity, participants are given the possibility to put into practice what they have learned through the previous activities: having acquired a deeper understanding of complex systems, they are able to adopt strategies in order to reach a certain preferable configuration for the system.

In our contemporary society, everything is intertwined and technology accelerates each process, so that it is impossible to make predictions on the effects of one's actions.

In *"Harvest"*, it is shown how one person's actions have consequences on an environment that is common to everyone, and thus on other people's life conditions.

This activity can help participants understand that, when dealing with a complex system, it is necessary to abandon the belief that a certain preferable configuration can result linearly from one's action, instead a strategy should be adopted: *"running mental models is a basic requirement for handling complexity in our everyday lives. We take complex scenarios in our mind and then run simulations in the head – implicit simulations. Subsequently we take appropriate decisions in a limited time. The results may not be optimal – but they can certainly be considered to be boundedly optimal. In other words, they are the best that we can come up with – given the limitations of time and resources – and their impact on our focus and attention"* (Niazi & Temkin, 2017).

In order to adopt a strategy, it is necessary to consider that causality in complex systems is non-linear, that the possible outcomes are only known from a statistical point of view, and that the dynamics of the system is not only due to the intertwined network of interactions among agents, but is also influenced by feedback mechanisms.

In *"Harvest"*, participants are invited to identify feedback loops in order to make predictions and adopt a certain strategy.

A first positive feedback loop raises from the fact that the teams that earn more money have the possibility to harvest more fish and thus become even richer.

A second reinforcing feedback loop can emerge if at the beginning of one turn the number of fish in the ocean is small: only a few fish can be harvested, and each team will earn more money per fish harvested, and thus will have the possibility to invest coins in order to harvest more fish in the following turn. Adopting this strategy would lead to a further reduction of the number of fish in the ocean.

Other two feedback loops – both negative – emerge from the rules of the game. The first one is due to the law of reproduction of fish, that is to say F/3 fish are added to the ocean if the number of fish available at the end of one round is F: the reduction of the number of fish due to fishing is balanced by reproduction.

The second negative feedback loop emerging, is the law of demand: *"the more we fish, the bigger is the offer and the smallest is price of each fish; this causes, at the following round, less fishing activity which brings to less offer and, then, to an higher price of fish, and so on. This feedback loop should be a deterrent against overfishing, so that the market price does not decrease"* (Barelli, 2017).

"Harvest" is not only a closing activity for the educational program we propose, but it also introduces an additional feature of complex systems that was not presented in the previous activities, but that is of paramount importance: in this activity the system composed of the teams of fisher is in relation with the external environment of the ocean and fish.

Conclusions

The idea of the present work derives from a strong personal interest on the theme of climate change, and from the awareness of the existence of difficulties in perceiving individual actions to be actually useful to tackle the issue. As a matter of fact, despite the growing of public concern on the issue of climate change, and of the awareness of the necessity to undertake actions in order to mitigate the phenomenon, the complexity of the issue causes fear and this can result in nonparticipation. Aiming at inducing pro-environmental behavior in individuals, the challenge should not be merely in explaining to people why they should undertake a certain action, but mostly in providing the necessary tools to understand the issue in its completeness. Indeed, climate is a typical example of a complex system, and the comprehension of its mechanisms is essential for reaching an increase of the public involvement in the process of mitigating the phenomenon of climate change. However, the understanding of the causal mechanisms of complex systems requires the gain of knowledge of new concepts that appear to be counter intuitive and that requires to enter a new causal logic. Several researches suggest that it is actually possible to provide a new systemic mindset to general public, and in particular this work focuses on the exploiting of role-playing activities for reaching this aim.

The four activities we proposed allow to convey the concepts of emergence, self-organization, and feedback, which help to explain how each individual behavior of an element of a complex system exerts influence on both the other elements and on the macroscopic properties. Also, the concept of attractor is introduced, which is useful to make people understand the necessity to use statistical tools to describe the climate. Finally, in the last activity participants are given the possibility to put into practice the knowledge on complexity they have acquired, and at the same time to realize that a mitigation strategy is effective only on an extended time scale.

The use of role-playing activities is only one example of didactical tool to convey concepts of complexity, however its power is in the fact that no preliminary scientific knowledge on formal aspects is necessary thus it can be proposed both at school and in other contexts, as well as to people of any age.

Although the four role-playing activities can be carried out independently, they can be included – either some or all of them, and in an order that is not *a priori* fixed – in a teaching path on complexity. This path will have to be designed accordingly to the age or school level of target participants, taking into account the formal, informal and non-formal context in which it will be carried out. In particular, it is crucial to make explicit the modelling procedure behind the construction of the role-playing activities: these activities – as well as the models on which they rely – contain aspects of simplification and reduction, and they cannot be considered precise descriptions of reality. Moreover, the teaching path will have to arrange the role-playing activities within other types of activities, such as lectures to introduce the mathematical basis of complexity, moments of guided exploration of computational simulations, discussions about the epistemological issues raised by this science and their role in our culture.

Indeed, the activities that have been proposed allow the introduction to the main conceptual aspects of complexity, however they do not provide knowledge on the technical and computational ones, which are fundamental tools for the advancements of this science.

In addition, not all the properties of complex systems are highlighted through the activities. In particular, among the missing features are all the ones linked to evolution such as deterministic chaos. This is not only due to the unavoidable limited duration of the game, but also to the impossibility to monitor exactly the trajectories and the evolution of each component of the system. A possible further improvement in this sense may be to design a game through which it is possible to understand how computational simulations are necessary tools to study the evolution of complex systems.

The suggested approach of addressing complexity through games should serve to foster both understanding and engagement with respect to the theme of climate change as well as, we guess, to induce a feeling of hope, the latter indeed based on the acquired awareness of the power of individuals to actually change the present dramatic situation.

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