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Playing the Rock-Scissors-Paper Game on Complex Networks in Ecology: Motivating Graduates to Learn Complex Networks*

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The Rock-Scissors-Paper is a game in which two players choose one out of three possible options: rock, scissors or paper. Rock breaks scissors, scissors cuts paper, and paper covers a rock. We use this game model to motive our students, with heterogeneous backgrounds, to obtain a basic knowledge of Complex Networks and Ecology. In particular, we analyze the behavior of the rock-scissors-paper model, a basic cyclic antagonist ecological model, played at different network topologies: random, scale-free and entangled. One of our main goals is that students scrutinize the topological properties determining optimal persistence of Biodiversity. In particular, our students have studied the extinction time of the 3 species when the size of the complex networks change, keeping the same properties in the nodes of the network. They have performed the simulations on networks with the same average degree <k> = 4, and with an initial random distribution of the species (rock, scissor, paper). Substantially different behaviors can be found playing in the different topologies. We want the students to understand the influence of the network topology in the outcome of the game; and more general the relevance of the underlying network topology in Game Theory.

Keywords: complex network; ecology; game theory; educational innovation

1. Introduction

This article is based in our experience in a Master course titled: Complex Networks in Ecology, where we teach both Ecology and Statistical Physics concepts. One of the main difficulties stems from the heterogeneous backgrounds of the students; some of them comes from Environmental Sciences and they are interested in Ecology, while some others comes from Engineering courses and are more interested in the Statistical Physics. With these constraints, we think that game models, in particular Rock-Scissors-Paper (RSP) model, played in a complex network is especially interesting for all of them.

The Rock-Scissors-Paper is a children's game in which two players choose one out of three options: rock, scissors or paper. Rock breaks scissors, scissors cuts paper, and paper covers a rock, so that each option prevails over another one; the game is symmetric in a cyclical way. In game theory, the simplest version of RSP can be described by the payoff matrix in Table 1.

Table 1. Payoff matrix of a Rock-Scissors-Paper game. Players can play three strategies

		Player 2		
		R	**S**	**P**
Player 1	**R**	0	1	-1
	S	-1	0	1
	P	1	-1	0

As an illustration, player 1 gains a point when playing rock (R) against scissors (S), but loses a point playing rock against paper (P). RSP is the simplest game in which the winner is decided by an intransitive dominance relationship between the game's moves. When the game is played with the same pure strategy (i.e. making always the same choice), none of the three has an intrinsic advantage [1].

We are especially interested in the RSP game because it has been used as a toy model in Ecology. This game exemplifies those systems in Ecology where three species cyclically dominate each other. RSP-type cycles can be observed directly in nature. One of the best-known examples, described by Sinervo and Lively [2], are the three different mating strategies of the lizard species *Uta stansburiana:*

- Orange-throated males are strongest and do not form strong pair bonds; instead, they fight blue-throated males for their females.

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- Yellow-throated males, however, manage to snatch females away from them for mating.
- Blue-throated males are middle-sized and form strong pair bonds. While they are out competed by orange-throated males, they can defend against yellow-throated ones. Yellow-throated males are smallest, and their coloration mimics females. Under this disguise, they can approach orange-throated males but not the stronger-bonding blue-throated specimens and mate while the orange-throats are engaged in fights.

This can be summarized as 'orange beats blue, blue beats yellow, and yellow beats orange', which is fully analogous to the rules of rock-scissors-paper [2]. Other similar interaction networks of many marine ecological communities involve three-species cycles [3].

On the other hand, the study of Ecology from the perspective of complex networks is originating a new framework to analyze the biological interactions [4]. The 'complex network' point of view permits to analyze the ecosystems taking into account the global structure of the network of the ecological interactions between the different species that constitute it. In particular, RSP has been used as a toy model to understand some ecological interaction as: invasion and coexistence of species. RSP model has been applied in a lattice 'landscape', but many ecosystems can be better understood as a complex network.

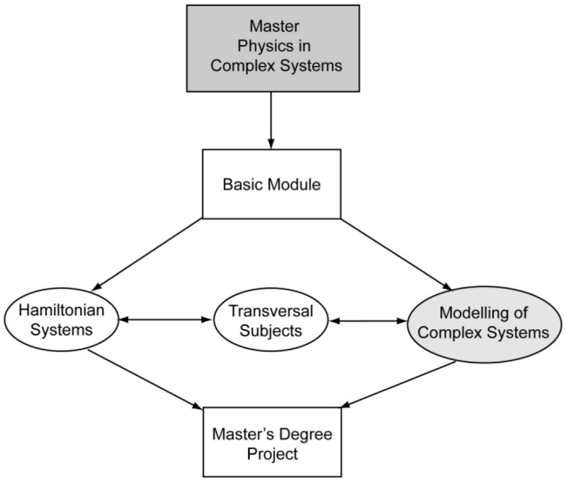

Fig. 1. University Master of Physics of Complex System curriculum at Technical University of Madrid (Universidad Politécnica de Madrid).

In this course, we want the students with heterogeneous backgrounds and interests in different subjects obtain a basic knowledge in complex networks and found the Ecology as an amazing framework to apply these ideas. The way to achieve our objective was to study the influence of the network topology in the outcome of the game; and more general the relevance of the underlying network topology in Game Theory. We analyze the behavior of the rock-scissors-paper model, a basic cyclic antagonist ecological model, playing at different network topologies: random, scale-free and entangled.

2. Framework of the course

Our course, titled 'Complex Networks in Ecology', is an elective subject into the University Master of Physics of Complex System at Technical University of Madrid (Universidad Politécnica de Madrid). This Master has an obligatory module and two different elective tracks: Hamiltonian Systems and Modelling of Complex Systems. A third module, titled 'Transversal subjects', has complementary subjects and seminars (see diagram in Fig. 1). Our graduate students can choose between two tracks in the curriculum: Hamiltonian Systems or Modeling of Complex Systems. Our subject is included in the Complex System module (Fig. 2).

This University Master's Degree is aimed at training a wide-ranging group of graduates in Science and Engineering with multidisciplinary subjects. This wide range of area of interests provides us with graduate students with heterogeneous backgrounds. With this constrain, we needed to find motivating and wide-range themes to involve them. We think game models could be an interesting subject to make a final project.

3. Games, payoffs and strategies

A game is an abstract formulation of an interactive decision situation with possibly conflicting interests. In game theory, normal form is a way of describing a game. It is usually represented by a matrix, which shows the players, strategies, and payoffs (see the example to the Table 1).

A strategy space for a player is the set of all

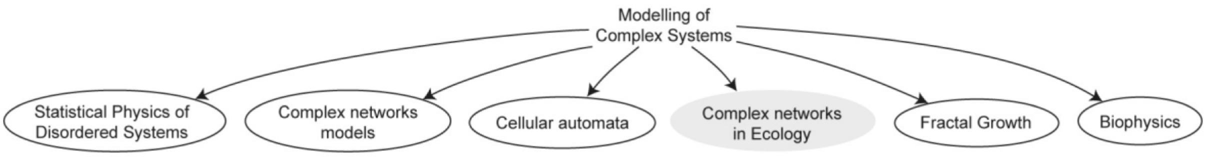

Fig. 2. Modelling of Complex Systems track curriculum. Our course, Complex networks in Ecology, is drawn with a grey background.

strategies available to that player, where a strategy is a complete plan of action for every stage of the game, regardless of whether that stage actually arises in play.

A payoff function for a player is a mapping from the cross-product of players' strategy spaces to that player's set of payoffs (normally the set of real numbers), i.e. the payoff function of a player takes as input a strategy profile (that is a specification of strategies for every player) and yields a representation of payoff as its output. When a game is presented in normal form, it is presumed that each player acts simultaneously or, at least, without knowing the actions of the other [1].

In particular, the application of game theory to interaction dependent strategy evolution in populations is called evolutionary game theory. Evolutionary game theory is useful in an ecological context by defining a framework of strategies in which adaptive features can be modeled. In 1973, Maynard-Smith and Price [5] define evolutionarily stable strategies as an application of theory of games to biological contexts. In evolutionary game theory, members of a population play pure strategies against each other, and reproduce in proportion to their relative success. This can lead to either coexistence of the all three strategies in constant proportions, or to endless oscillations in their populations [6].

We have chosen the RSP game. Here there are two players; one chooses the row and the other chooses the column. Each player has three strategies, which are specified by the number of rows and the number of columns. The payoffs are provided in Table 1. Several extensions of this game have been invented.

The RSP model in a lattice has been studied by Frean and Abrahamm [7]. They realized a complete study of this model. They consider a system with three species in a competitive loop and show that this simple ecology exhibits two counter-intuitive phenomena. First, the species that is least competitive is expected to have the largest population and, where there are oscillations in a finite population, to be the least likely to die out. As a consequence an apparent weakening of a species leads to an increase in its population. Second, evolution favors the most competitive individuals within a species, which leads to a decline in its population.

4. Complex networks

The study of complex networks pervades all of science, from neurobiology to statistical physics. Systems susceptible to be visualized as networks abound in Nature and in man-made world. In recent years a lot of networks such as the Internet, the World Wide Web, and social, economics and biological networks of various types have been studied [8].

A network is a set of vertices, or nodes, with connections between them, called edges or links. The nodes can represent different things, from actors to scientist in social networks; from genes to neurons in biology; from individuals in a population to species in a community in Ecology. Edges usually represent some kind of interaction between nodes, including movies in the actors, citations in the scientists' papers, transcriptional control and species interactions.

The study of the networks, in the mathematical graph theory, has had a long history. It is often cited the first step in this discipline in 1736 with the Konigsberg Bridge Problem resolved by Leonard Euler [8]. In the 30s, sociologists realized the importance of the network perspective in the Social Sciences. Recently, we have witnessed an upsurge of research on networks. This has been prompted by the availability of new large database and more powerful computers that allow analyzing on large scales.

Why is network anatomy so important to analyze? Because structure always affects function. For instance, the topology of a computer networks affects the spread of a computer virus. From this point of view, the current interest in networks is part of research on complex systems.

The degree distribution is a way to measure of the structure of a network. A node is characterized by its degree, which is defined as the number of links to other nodes. In this way, the degree distribution is the frequency distribution of the number of links per node. We define p_k as the fraction of the nodes in the network that have degree k, and normalized it means the probability of finding a node in the network with degree k.

For example, Erdös-Renyi's random graphs are characterized by a degree distribution with a Poisson distribution. In these networks, large number of nodes has a similar degree around the mean degree. Conversely, many examples of complex networks are more heterogeneous, showing a power-law degree distribution. In these networks, all scales of nodes are presented. The bulk of the nodes has a few interactions, but a few nodes are highly connected, these nodes are called 'hubs'. These nodes carry out a fundamental role in the network.

In particular, we are interested in biological networks. There is a big number of biological systems can be represented as networks; from network of metabolic pathways or genetic regulatory network to food webs. In this course, we study the network relative to the Ecology: food webs [9-10] and mutualistic networks [11].

Food webs are used to represent a type of ecological interaction called predator-prey. Nodes represent species in an ecosystem and a directed edge from species B (prey) to species A (predator) indicates that A feeds on B. Other ecological symbiosis as parasitism can be represented by food webs. Statistical studies of food webs carried out by different groups: Solé [12–13], Amaral [14] and Martinez [15–16], among others.

Mutualistic networks represent a type of ecological interaction called mutualism. Here, nodes again represent species in an ecosystem and an undirected edge from specie A (usually an animal) to species B (usually plants) indicates that the animal A is a pollinator or seed disperser of the plant B. A classical reference of this type of networks is the work carried out by Jordano et al. [17] or recently Bastolla et al. [4].

We have recommended to our students three types of bibliography to understand the complex networks: reviews, popular books and technical books. A number of excellent reviews on Complex Networks have appeared recently in the literature. Newman [18], Albert and Barabási [19] and Dorogovtsev and Mendes [20] have given comprehensive pedagogical reviews. A worthwhile review about mutualistic networks was written by Bascompte and Jordano [11]. The popular books on the subject of networks we have mentioned are: 'Linked' by Barabási [21] focused on the Barabási's work on scale-free networks. Watt's 'Six Degrees' [22] shows a historical view of the discoveries. The number of more technical books is huge. We have used the book edited by Newman, Barabási, and Watts [8]. This book presents a collection of the most worthwhile published papers and also contains a useful review. More specific books on Food webs are the published by Cohen et al. [9], and more recent by Pimm [10].

5. Methodology

We started the introduction about complex networks watching a documentary movie, titled: 'How Kevin Bacon cured cancer' [23] (duration: 20'). Annamaria Talas directed this documentary about the 'complex networks'. The documentary go over some properties of the complex networks as 'small world' [8], based on the idea that anyone on the planet can be connected in just a few steps of association. 'How Kevin Bacon Cured Cancer' brings us a new view of the World. Through this documentary we discover it's at the heart of a major scientific breakthrough. We think that watching the movie is a good 'warm up' to our students to get familiar with this new topic.

We started the first lectures, explaining the subjects regarded to basic ideas of complex networks and the applications in Ecology. In the second part of the course the students have to develop a work using the topics explained in the first part of this course.

To achieve our objective, the students studied the influence of the network topology in the outcome of the game. We propose to the students to analyze the behavior of the rock-scissors-paper model, playing at different network topologies: random, scale-free and entangled. One of our main goals could be to scrutinize the topological properties determining optimal persistence of Biodiversity. In particular, our students had to study the extinction time of the 3 species when the size of the complex networks change, keeping the same properties in the nodes of the network.

We started studying three classical networks with different topologies: Random graph [24], Barabási-Albert [25], and Entangled [26]. These networks show different degree distributions: Poisson in the limit of the large graph size, power-law distributed, and delta-like (i.e. the network is regular or almost-regular), respectively. We want the students understand the influence of the topology in the outcome of the game. These three kinds of networks will be the 'landscape' or 'substrate' on the top of which the RSP model will be played.

The students wrote programs (preferable as Matlab scripts, although some students would rather program in C++, Java or Visual Basic) to generate the simplest networks: random graph and Barabási-Albert network. Entangled network needs a more accurate programming knowledge and these networks were calculated by the teachers [26]. Then, we have calculated the degree distribution of these networks topologies to verify the networks properties. This approach permitted our students an active approximation to the complex networks.

Figure 3 shows the three networks used in our work. The three plots have the same number of nodes 100 and they were generated with the same average degree, $<k> = 4$. This degree corresponds to the number of nearest neighbor sites in a regular lattice. We have used networks with the same average degree to make a good comparison. This plot was made using the software 'gephi' [27]. We explained this software in a tutorial class.

In the second step, we want that our students programming a Rock-Scissors-Paper model playing first in a lattice and then in the different above-mentioned topologies. Although we are interested in the classical version of the RSP model, some extensions of this model have been proposed. These may allow further choices, for example in the 8th episode of the second season of the American comedy television series: 'The Big Bang Theory' titled: 'The Lizard-Spock Expansion' [28]. Actors

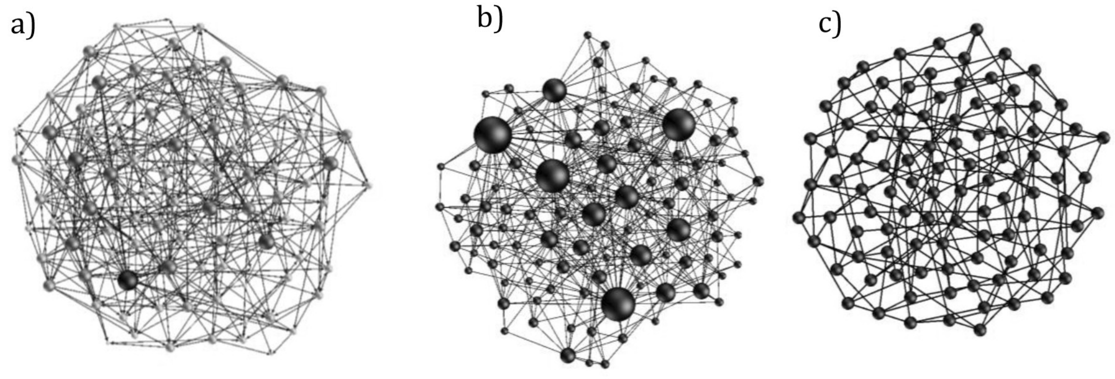

Fig. 3. Students have performed computer simulations in three different networks topologies: (a) Erdos-Renyi random, (b) Barabási-Albert scale free, and (c) Entangled network. To be compared we have worked with networks with the same number of nodes, 100, and with the same average degree, <k> = 4. Node size is proportional to its degree.

play Rock-Scissors-Paper-Spock-Lizard, a Sam Kass's expanded form of the game [29]. Each item beats two others and is beaten by the remaining two ones, that is, scissors cut paper covers rock crushes lizard poisons Spock smashes scissors decapitate lizard eats paper disproves Spokes vaporizes rock crushes scissors [1]. To start this topic we, students and teachers, watched the episode and the students expressed several hypotheses based on the RSP model of which need to be experimentally proved.

We proposed to write the scripts to play RSP model in a nearest neighbor lattice as a part of the project. Initially, to play game models the fixed interaction network is defined by the sites of a lattice and the edges between those pair whose distance does not exceed a given value. The most frequently used structure is the square lattice with the von Neumann neighborhood (connections between nearest neighbor sites z=4). In particular, we are interested in the extinction time of the species. The students represented the three species versus the time. Initial distribution of species was random with the same percentage. The species fluctuate.

With this approximation our students become familiar with the various concepts covered by the course. These codes can be placed at the students' disposal thanks to b-Learning platforms such as Moodle, which allow students to revise the acquired concepts. In a tutorial class, we chose the best scripts, sometimes mixing different codes, to play RSP in the complex networks.

In the last step, students with the best-programmed scripts, assembled in a single code to play RSP model in the complex networks. The students were divided by groups depending of different topologies and system sizes. We have had three groups: Barabási-Albert, Erdos-Renyi, and Entangled. Every group had to run the RSP model in their topology with, at least, three different networks sizes.

6. Main results

In the last part of the course, we wanted the students worked in the project: 'making a little research', applying the now acquired knowledge about complex networks. We think the best way is making a little research. In particular, the students were interested in studying the extinction time as a function of network system size. Figure 4 shows the results of the three groups in one plot. All results are averaged over 200 realizations. We can see the distribution of the extinction time versus number of nodes in three different network topologies: Random Erdos-Renyi (circles), scale-free (diamonds), and entangled (squares).

It is worth noting that we found a really different behavior of the extinction time in the Barabási-Albert scale free network. Figure 5 illustrates power law distributions of the extinction time as a function of system size in random and entangled networks.

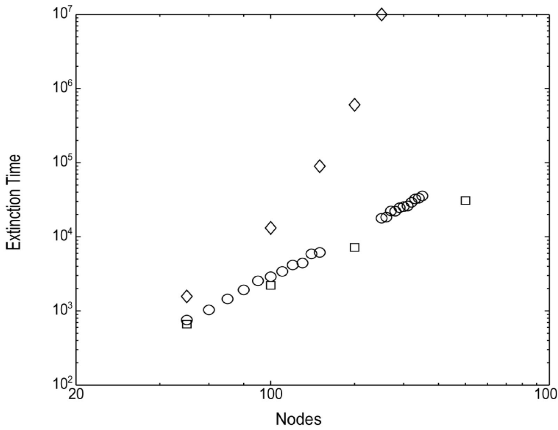

Fig. 4. Distribution of the extinction time versus the number of nodes of the network for the three different topologies studied in our work. All networks have the same average degree, <k> = 4. Diamonds, circles, and squares represent extinction time in a Barabási-Albert, Random and Entangled networks, respectively.

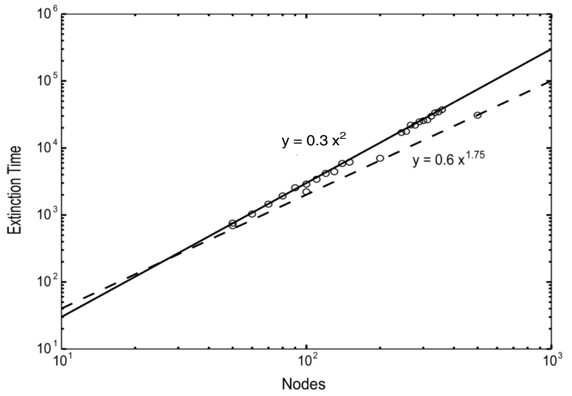

Fig. 5. Extinction time function of the number of nodes for random graph and entangled networks. Solid and dashed lines show the best power-law fits with exponent of 2 and 1.75, respectively.

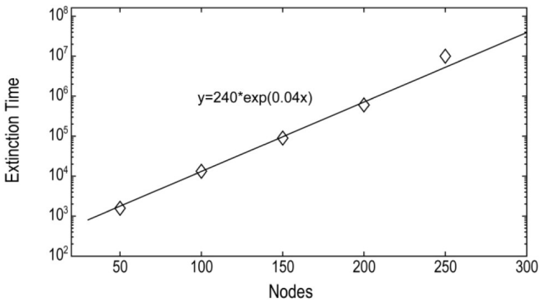

Fig. 6. Extinction time as function of the number of nodes. Exponential distribution has been found in this topology. Solid line shows the best fit with an exponent of 0.04.

The solid line and dashed line show power law fits with exponents 2 and 1.75 in random and entangled networks, respectively.

On the other hand, Fig. 6 shows an exponential distribution of the extinction time versus number of nodes in scale-free networks. The solid line shows an exponential fit with an exponent 0.04.

These results had not been showed in the complex networks literature. It is very reasonable the exponent in the entangled networks, 1.75, is less than the other one for the random network 2, because entangled network was designed to optimize the interaction between nodes. Actually, almost all nodes have the same degree, and consequently entangled network are more connected than random networks. In this case, the extinction of the species is achieved easily in entangled networks.

More difficult to understand is the result obtained with the Barabási-Albert network. First of all, we have found an exponential distribution between extinction time and numbers of nodes. This behavior is different than obtained with the others networks. From of point of view of biodiversity and ecosystem interactions, this topology could be the optimum to the stable interactions of the species.

As summary, students verified that the topology of the interactions could change the evolution of biodiversity. After comparing the results they tried to explain why the Barabási-Albert network seems to show the best results of extinction time.

From the academic point of view, when we described this methodology to students they were very interested in their tasks and they had always good disposition. As result of the learning process, the students achieved a good comprehension of complex network and the importance of topology in the biodiversity context. We collected the opinions of the students when the course finished. All of them showed a great pleasure in the development of the course. They agreed that making a little ‘research work’ is a very stimulating way for acquiring new concepts and working on it.

7. Conclusions

We have reported on our experience in the University Master’s Degree in Physics on Complex Systems, in particular, in the course titled: Complex Networks in Ecology. Our main disadvantage was the heterogeneous backgrounds of the students, coming from Environmental Sciences and Physics or Engineering. Students coming from Environmental Sciences have a good background in Ecology and Biology, while students coming from Engineering or Physics are good prepared in Statistical Physics. Our solution was to find a subject interesting to all of them. We think that game models, in particular Rock-Scissors-Paper model, played in a complex network are especially suitable for this purpose.

Students have programmed different scripts to simulate a Rock-Scissors-Paper game model and to generate networks with different topologies: Random and Barabási-Albert. The students have written the codes and compare between them is a positive option to motivate an active learning. We use Moodle platform to exchange the codes. This b-learning platform, through forums, was also really useful to maintain an active interaction between students and teachers.

We would like to emphasize particular aspects in our experience. First, we have used movies to start the introduction of new topics. This ingredient in our ‘recipe’ was fundamental to motive an active approach to the course. And second, the idea to perform a research with new results was ‘the icing on the cake’ in our recipe. All the students assess very positively their experience in this course.

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