Complex Networks of Mindful Entities

LUÍS MONIZ PEREIRA

Centro de Inteligência Artificial — CENTRIA
Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa
2829-516 Caparica, Portugal

Abstract

The mechanisms of emergence and evolution of cooperation — in populations of abstract individuals with diverse behavioural strategies in co-presence — have been undergoing mathematical study via Evolutionary Game Theory, inspired in part on Evolutionary Psychology. Their systematic study resorts as well to implementation and simulation techniques in parallel computers, thus enabling the study of aforesaid mechanisms under a variety of conditions, parameters, and alternative virtual games. The theoretical and experimental results have continually been surprising, rewarding, and promising.

Recently, in our own work we have initiated the introduction, in such groups of individuals, of cognitive abilities inspired on techniques and theories of Artificial Intelligence, namely those pertaining to Intention Recognition, encompassing the modelling and implementation of a tolerance/intolerance to errors in others — whether deliberate or not — and tolerance/intolerance to possible communication noise. As a result, both the emergence and stability of cooperation, in said groups of distinct abstract individuals, become reinforced comparatively to the absence of such cognitive abilities.

The present paper aims to sensitize the reader to these Evolutionary Game Theory based studies and issues, which are accruing in importance for the modelling of minds with machines. And to draw attention to our own newly published results, for the first time introducing the use of Intention Recognition in this context, with impact on mutual tolerance.

Keywords: Evolutionary Game Theory; Evolutionary Psychology;
Intention Recognition; Tolerance.

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Within our research on these networks we intend to understand, and explain, how some social collective behaviours emerge from the cognitive capabilities of individual agents, in communities where said individuals are nodes of complex adaptive networks, which self-organize as a result of the referred cognition of individual agents. Consequently, we need to investigate which cognitive abilities have an impact on the emergence of properties of the population and, as a result, which cognitive abilities determine the emergence of which specified social collective behaviours. Hence, the key innovation consists in the articulation of two distinct levels of simulation, individual and social, and in their combined dynamics. This needs to be reified both at the modelling level as well as at the computational implementation one.

Biological evolution is characterized by a set of highly braided processes, which produce a kind of extraordinarily complex combinatorial innovation. A generic term frequently used to describe this vast category of spontaneous, and weakly predictable, order generating processes, is «emergence». This term became a kind of signal to refer the paradigms of research sensitive to systemic factors. Complex dynamic systems can spontaneously assume patterns of ordered behaviours which are not previously imaginable from the properties of their composing elements nor from their interaction patterns. There is unpredictability in self-organizing phenomena — preferably called «evolutionary» —, with considerably diverse and variable levels of complexity.

What does emerge? The answer is not something defined but instead something like a shape, pattern, or function. The concept of emergence is applicable to phenomena in which the relational properties predominate over the properties of composing elements in the determination of the ensemble's characteristics. Emergence processes appear due to configurations and topologies, not to properties of elements (Deacon, 2003).

As we have remarked before, two hundred years after the birth of Darwin, and 150 after the *On the Origin of Species*, several fundamental questions about evolution still remain unanswered. The problem of evolution of cooperation and of the emergence of collective action — cutting across areas as diverse as Biology, Economy, Artificial Intelligence, Political Science, or Psychology — is one of the greatest interdisciplinary challenges science faces today. To understand the evolutionary mechanisms that promote and keep cooperative behaviour is all the more complex as increasingly intricate is the intrinsic complexity of the partaking individuals. «Complexity» refers to the study of the emergence of collective properties in systems with many interdependent components. These components can be atoms or macromolecules in a physical or biological context, and people, machines or organizations in a socioeconomic context.

This complexity has been explored in recent works, where it is shown, amongst several other properties, that the diversity associated with structures of interaction, of learning and reproduction of a population, is determinant for the choices of agents and, in particular, to the establishment of cooperation actions (Santos *et al*., 2006, 2008). These studies were based on the frame of reference provided by Evolutionary Game Theory (Maynard-Smith, 1982) — alluded to before — and by the theories of Science of Networks (Dorogotsev & Mendes, 2003), combining instruments for modelling multi-agent systems and complex adaptive systems.

«Egotism» concerns the logic behind the unending give-and-take that pervades our societal lives. It does not mean blind greed, but instead an informed individual interest. Thus, «the evolution of cooperation» has been considered one of the most challenging problems of the century. Throughout the ages, the issue of self-consideration versus "the other"-consideration has fascinated thinkers, but the use of formal models and experimental games is relatively recent. Since Robert Trivers (Trivers, 1971) introduced the evolutionary approach to reciprocity, games have served as models to explore the issue.

The modelling of artificial societies based on the individual has significantly expanded the scope of game theory. Societies are composed by fictitious subjects, each equipped with a strategy specified by a program. Individuals meet in randomized pairs, in a joint iterated game.

The comparison of accumulated rewards is used to update the population: the most successful individuals produce more offspring, which inherit their strategy. Alternatively, instead of inheriting strategies, new individuals may adapt by copying, from known individuals, the strategies that had best results. In both cases, the frequency of each strategy in the population changes over time, and the ensemble may evolve towards a stable situation. There is also the possibility of introducing small mutations in minority, and study how they spread.

Evolutionary Game Theory (EGT) is necessary to understand the why and the how of what it takes for agents with individual interests to cooperate for a common weal. EGT emphasizes the deterministic dynamics and the stochastic processes. Repeated interactions allow the exploration of direct reciprocity between two players (Sigmund, 2010).

In the EGT approach, the most successful strategies become more frequent in the population. Kinship, neighbourhood relationships, and individual differences, may or may not be considered. In indirect reciprocity (Nowak & Sigmund, 2005), players interact at most once, but they have knowledge of their partners' past behaviour. This introduces the concern with reputation, and eventually with moral judgment (Pacheco *et al.*, 2006; Pereira & Saptawijaya, 2011).

The strategies based on the evaluation of interactions between third parties allow the emergence of kinds of cooperation that are immune to exploitation, because then interactions are channelled just to those who cooperate. Questions of justice and trust, with their negative (punishment) and positive (help) incentives, are fundamental in games with large diversified groups of individuals gifted with intention recognition capabilities. In allowing them to choose amongst distinct behaviours based on suggestive information about the intentions of their interaction partners, they are, in turn, influenced by the behaviour of the individual himself, and are also influenced by the tolerance to error and to noise in the communication. One hopes understanding these capabilities can be transformed into mechanisms for spontaneous organization and control of swarms of autonomous robotic agents.

With this objective, we have studied the way players' strategies adapt in populations involved in cooperation games. We used the techniques of EGT, considered games such as the «Prisoner's Dilemma» and «Stag Hunt», and showed how the actors participating in repeated iterations in these games can benefit from having the ability to recognize the intentions of other actors, thereby leading to an evolutionary stable increase in cooperation (Han & Pereira & Santos, 2011, 2011a), compared to extant best strategies.

Intention recognition is implemented using «Bayesian Networks» (BN) (Pereira and Han, 2011) and taking into account the information of current signals of intent, as well as the trust and tolerance built from previous plays. We experimented with populations with different proportions of diverse strategies in order to calculate, in particular, what is the minimum fraction of individuals with Intention Recognition for cooperation to emerge, invade, prevail, and persist. It seems to us that Intention Recognition, and its use in the scope of tolerance, is a foundational cornerstone where we should begin at, naturally followed by the capacity to establish and honour «commitments», as a tool towards the successive construction of collective intentions and social organization (Searl, 2010).

We have argued that the study of these issues in minds with machines has come of age and is ripe with research opportunities, and have also communicated some of the published inroads we have achieved with respect to intention recognition and tolerance in the evolutionary game theory context.

References (Author's works available at http://centria.di.fct.unl.pt/~lmp/publications/Biblio.html)

Deacon, T.W. (2003). The Hierarchic Logic of Emergence: Untangling the Interdependence of Evolution and Self-Organization, in: Weber, H.W. & Depew, D.J., *Evolution and Learning: The Baldwin Effect Reconsidered*. Cambridge: MIT Press.

Dorogotsev, S.N., Mendes, J.F.F. (2003). *Evolution of Networks: From Biological Nets to the Internet and WWW*. Oxford: Oxford University Press.

Han, T.A., Pereira, L.M., Santos, F.C. (2011). Intention Recognition Promotes The Emergence of Cooperation. *Adaptive Behaviour*, 19(3):264-279, August 2011.

Han, T.A., Pereira, L.M., Santos, F.C. (2011a). *The role of intention recognition in the evolution of cooperative behaviour*, in: Procs. Intl. Joint Conf. on Artificial Intelligence (IJCAI 2011), pp. 1684-1689, July 2011, Barcelona, Spain.

Maynard-Smith, J. (1982). *Evolution and the Theory of Games*. Cambridge: Cambridge University Press.

Nowak, M.A., Sigmund, K. (2005). Evolution of indirect reciprocity. *Nature*, 437, 1291-8.

Pacheco, J.M., Santos, F.C., Chalub, F.A. (2006). Stern-judging: A simple, successful norm which promotes cooperation under indirect reciprocity. *PLoS Comput. Biol.*, 2, e178.

Pereira, L.M., Saptawijaya, A. (2011). Modelling Morality with Prospective Logic, in: M. Anderson, S. L. Anderson (eds.), *Machine Ethics*, Cambridge: Cambridge University Press.

Pereira, L.M., Han, T.A. (2011). Intention Recognition with Evolution Prospection and Causal Bayesian Networks, in: A. Madureira, J. Ferreira, Z. Vale (eds.), *Computational Intelligence for Engineering Systems: Emergent Applications*, pp. 1-33, Berlin: Springer.

Santos, F.C., Pacheco, J.M., Lenaerts, T. (2006). Evolutionary dynamics of social dilemmas in structured heterogeneous populations. *Proc. Natl. Acad. Sci. U S A,*103, 3490-4.

Santos, F.C., Santos, M.D., Pacheco, J.M. (2008). Social diversity promotes the emergence of cooperation in public goods games. *Nature*, 454, 213-6.

Searl, J. (2010). *Making the Social World: The Structure of Human Civilization*. Oxford: Oxford University Press.

Sigmund, K. (2010). *The Calculus of Selfishness*. Princeton: Princeton University Press.

Trivers, R.L. (1971). The evolution of reciprocal altruism. *Quarterly Review of Biology*, 46, 35-57.