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Phenomenological theory of collective decision-making

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HIGHLIGHTS

- Quantitative formalism of complex collective decision-making scenarios is proposed.
- We search for the optimal competence distribution of heterogeneous agents.
- The best groups have at least one specialist for each sub-problem.
- The specialists have some insight into other sub-problems as well.
- Good agreement with empirical results obtained from large-scale citation database.

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ABSTRACT

An essential task of groups is to provide efficient solutions for the complex problems they face. Indeed, considerable efforts have been devoted to the question of collective decision-making related to problems involving a single dominant feature. Here we introduce a quantitative formalism for finding the optimal distribution of the group members' competences in the more typical case when the underlying problem is complex, i.e., multidimensional. Thus, we consider teams that are aiming at obtaining the best possible answer to a problem having a number of independent sub-problems. Our approach is based on a generic scheme for the process of evaluating the proposed solutions (i.e., negotiation). We demonstrate that the best performing groups have at least one specialist for each sub-problem — but a far less intuitive result is that finding the optimal solution by the interacting group members requires that the specialists also have some insight into the sub-problems beyond their unique field(s). We present empirical results obtained by using a large-scale database of citations being in good agreement with the above theory. The framework we have developed can easily be adapted to a variety of realistic situations since taking into account the weights of the sub-problems, the opinions or the relations of the group is straightforward. Consequently, our method can be used in several contexts, especially when the optimal composition of a group of decision-makers is designed.

1. Introduction

Addressing the process of collective decision making has represented a great scientific challenge for a long time [1–4]. It is a highly relevant aspect of the behavior of social groups, in particular, because as it has been argued, measured and shown analytically: the "wisdom of crowds" can go qualitatively beyond that of the individuals' [2].

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This statement also holds for animal assemblies [5–7]. A rarely considered, but essential case is when the problem to be solved is complex, i.e., has many facets. Under such conditions the quality of the collective solution is highly influenced by the composition of the group. Obviously, if the members of the group are identical, the group's performance can hardly go beyond that of any of its member's. However, if the problem to be solved is complex – i.e., has a number of different aspects or "dimensions" [8] – a group having members specialized in their respective kinds of sub-problems is expected to be much more efficient in providing a high quality answer, than a uniform one. The stress is on the independent nature of the sub-problems, making the problem high-dimensional. In a way our present work can be considered as a quantitative approach to the problem of division of labor [9,10] in the context of collective decision making (the task/labor is to bring about a decision; the division is made among the specialists of the sub-problems).

In spite of the above almost trivial observation regarding heterogeneous, diverse or "multidimensional" groups, a quantitative demonstration of its validity needs a carefully constructed framework. Prior works involving quantitative analysis have almost exclusively focused on problems that could be regarded as "one-dimensional" [2,11–13] from our point of view which considers a problem having several dimensions (being multidimensional) if it can be broken down into sub-problems, each having its own characteristic feature independent of those of the others'. In the case of one-dimensional problems it has been demonstrated – using approaches from theory (see, e.g., the pioneering works [11,13]) through genetic optimization [13] to agent based modeling/simulations [14] and observations [15,16] – that diverse groups can outperform homogeneous ones.

Intuition suggests that a group of specialists (one competent person for each sub-problem) should be optimal regarding the quality of the solution with the constraint of minimizing costs at the same time. Here we present a generic agent-based approach which – due to its minimal assumptions – quantitatively demonstrates that the breadth of knowledge of its members makes a group more efficient, i.e., being capable of using a smaller amount of resources to produce a more beneficial solution in a wide variety of potential applications. This is what corresponds to the "synergy" resulting in a better decision relative to the one following from a simple "linear" aggregation of the proposed solutions. And what we show in our work is how this synergy can emerge from a negotiation process. Naturally, negotiation is absent (generally) in animal societies. Specialization is the result of age or hormone level etc.

Many opinion formation models exist in the contemporary literature, among which many considers "heterogeneous" agents as well, often with continuous opinion values (for a review see [17]). However, agents in these studies are usually heterogeneous regarding their (i) confidence thresholds (or bounds of confidence, meaning that interacting agents adjust their opinions towards that of the others, but only if the two opinions are closer to each other than a certain threshold, a phenomenon closely related to the one called homophily), (ii) conviction, or (iii) influencing ability (aka. social influence). In contrast, our agents are homogeneous with respect to the above mentioned characteristics, but they are heterogeneous regarding their abilities, and what is more, their entire spectrum of abilities.

Other fundamental differences between the opinion formation models in contemporary literature and our approach include the followings:

- Most of them consider two-valued opinions (0/1, yes/no, etc.), motivated by the Ising-model. Their popularity is due to their simplicity, despite which they can lead to very deep results [18].
- Most contemporary models assume a *simple* update rule: a (usually randomly selected) agent simply changes opinion "suitably" to its neighbors. For example, if some neighbors of the selected agent share an opinion, the focal agent simply adopts it. In contrast, we detail the mechanism of "convincing": how it happens in iterative rounds with members evaluating the proposals of others and discussing it, all of which is affected by personal abilities.
- Contemporary models usually consider entire societies (often even assuming that $N \rightarrow \infty$), with mostly binary interactions. In contrast, we consider a relative small group ($N \approx 10$), but with intense interaction, in which all members participate.
- The aim of the above mention models is usually to gain an insight of the *spread and dynamics* of opinions, with emphasis on occurrent consensus or stalemate situations. In contrast, *we aim to find the optimal composition of a group, regarding the characteristics of the members*—in this case, (multidimensional) abilities.

A paradigmatic example for our approach is that of a board of directors for a large company (however, there are many other possible examples ranging from a group of animals searching for resources up to a government or simply a team carrying out interdisciplinary research). In the case of a board of directors a potential candidate problem is that of finding the best possible placement and product for a new factory. Obviously, the various aspects of this problem are quite diverse, each of them requiring specific knowledge, i.e., the decision involves knowledge of the history of the given country, various features of the labor force (education, etc.), geographical and logistic conditions, potential market in the region, and so on. It is an important feature of the situation that the members of the group cannot get any information about the quality of their propositions from an "outsider" who could know the optimal solution *ab ovo*.

2. The model

2.1. Formalizing interdisciplinary decision-making

We have aimed at a model that is simple, but is still appropriate for projecting a wide class of realistic situations onto it. In order to do so, we consider groups of N individuals solving a problem P having M sub-problems P_j ($j = 1, 2, \ldots, M$)