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Recent Developments in Granular Computing:
A Bibliometrics Study

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Abstract

This is a follow-up of the paper "A ten-year review of granular computing" published in 2007. We will continue to examine the most influential papers in granular computing. Based on the analysis of the impact papers, a list of key issues of granular computing research is given. We also summarize recent developments of research in granular computing.

1 Introduction

Granular computing (GrC) is a new paradigm in information processing. Granulation of a universe involves dividing the universe into subsets or grouping individual objects into clusters. In the paper entitled *A ten-year review of granular computing* [25] presented in last year's granular computing conference, I mainly identified prolific authors, impact authors, and research articles with the most impact in granular computing. As stated in Wohlin's article, "Citations are a common way of judging the most influential work in different fields. The most cited articles often provide new insights, open a new avenue of research, or provide a significant summary of the state-of-the-art in an area. Citations are a way to show how researchers build their work on existing research to evolve research further. Basically, they are the backbone of research and hence articles and authors being cited frequently deserve acknowledgment for their contribution" [22].

The aim of this article is to observe, analyze and understand the current developments and future directions based on Bibliometrics results of granular computing research. We will update metrics regarding the most influential papers identified in [25] in the next section. In Section 3, we cluster them based on on our findings and identify some research issues in granular computing. We will further examine other influential and important works in line with our findings and suggestions in Section 4.

2 The Most Influential Papers

We have identified 15 research articles that have had the largest impact on the research of granular computing [25]. As 2007 was considered the 10th year since the birth of granular computing, we may gain more understanding of the developments of granular computing by analyzing these papers. Table 1 presents the rankings of these most influential papers. The data was collected from ISI's Web of Science during June 13 to 19, 2008. We used the terms "granular computing", "information granularity", "information granulation" or "granular computation" in the Topic field to identify granular computing papers [25]. The first three The columns 2 and 3 list the papers and their total citation counts in 2008. The first column gives their rankings regarding to citations. In addition, the rankings of the papers in the previous search are presented in the brackets. The last two columns show the changes of ranking and citation counts since our previous search, which was conducted during April 27 to May 5, 2007.

It is interesting to know that the top 15 papers are still the same as in 2007. Furthermore, the rankings are also more or less the same. In particular, Pedrycz *et al.* 1999 [14] and Skowron *et al.* 2001 [17] swaped positions, as did Hirota *et al.* 1999 [6] and Greco *et al.* 2000 [2]. The only big change is that the position of Pal *et al.* 2004 [10] was changed from 14 to 12. Reference [13] has also received 10 citations (it was 8 in 2007) and could be included in our list as number 15 (tied).

On the bottom row, the total citation number for these influential papers is 495 citations as of 2008. There are 75 new citations during a slightly more than one year's period. The citation count was 420 in our 2007 research. Further examination found that 45 newly published scientific arti-

Table 1. Rank of Top Cited Papers

Rank (Previous Rank)	1997-2008 Influence Papers	No. of Citations	Ranking Change	Citations Change
1 (1)	Zadeh 1997 [31]	183	0	+23
2 (2)	Creco *et al.* 2001 [3]	79	0	+14
3 (4)	Pedrycz *et al.* 1999 [14]	31	+1	+8
4 (3)	Skowron *et al.* 2001 [17]	28	-1	+2
5 (6)	Pedrycz *et al.* 2001 [11]	23	+1	+6
5 (5)	Yao 2001 [26]	23	-1	+5
7 (7)	Hirota *et al.* 1999 [5]	18	0	+1
8 (8)	Peters *et al.* 2003 [16]	17	0	+1
9 (10)	Hirota *et al.* 1999 [6]	16	+1	+3
10 (9)	Greco *et al.* 2000 [2]	15	-1	+2
11 (14)	Pal *et al.* 2004 [10]	14	+3	+5
12 (11)	Hata *et al.* 2000 [4]	13	-1	+1
12 (11)	Slowinski *et al.* 2002 [20]	13	-1	+1
14 (13)	Pedrycz *et al.* 2002 [12]	12	-1	+2
15 (15)	Yao 2003 [27]	10	0	+1
	Total Citations	495		+75

cles cited the 15 most influential papers during this time period.

3 The Most Influential Papers and Beyond

Most of the highly-cited granular computing papers are fuzzy sets and rough sets related. These papers were published from 1997 to 2004. If we more closely examine the time, we may find that the papers published in early years are fuzzy-related while the papers published in later years are rough set oriented. To be exact, of the 6 papers published from 1997-2000, 5 of them are fuzzy sets papers. Of 8 papers published from 2001 to 2003, 6 are rough sets papers. The papers published in 2004 covers both fuzzy sets and rough sets. In fact, [16] are also fuzzy sets and rough sets related.

3.1 Influential Paper Clusters

A simple cluster-oriented view of these papers could be fuzzy, rough and application.

Fuzzy Aspects of Granular Computing It is obvious that the pioneer work of Zadeh [31] is fuzzy oriented. It introduced a fuzzy logic view of information granulation and human reasoning. The works from Pedrycz's team are mainly on studies of incorporating fuzzy sets with granular computing and their applications in data mining [5, 11, 12]. Paper [14] deals at a more abstract level, i.e., human centered, fuzzy models for information processing. Peters's paper [16] and Pal's paper [10] are also both fuzzy and rough related.

Rough Aspects of Granular Computing The research by Slowinski's team is mainly on multi-criteria decision making with rough sets [2, 3, 20]. The key benefit of their approach is to allow us to deal with inconsistencies typical to the consideration of criteria and preference-ordered decision classes. Skowron and Peters eliminated the fundamentals of granular computing [16, 17]. [16] examined approximation spaces with the aim for pattern generation and the discovery of patterns for target concept approximation. [17] introduced information granule syntax and semantics as well as the similarity relations of granules for knowledge discovery and reasoning. Yao on focused stratified and probabilistic approximations based on hierarchical granulation [26, 27]. It is argued that decision theory should play a key role in rule induction when using rough set theory. A more recent summary of decision-theoretic rough set models can be found in [28].

Granular Computing Applications Although most of the influential papers emphasize more on theoretical aspects, it is clear that they are aimed for data analysis, decision making and data mining. Two more application-oriented papers are [4] and [6], both of them dealing with image processing.

The clustering is also in line with our observations to the recent scientific articles that cited the most influential papers. As we can see from the previous section, there are 45 papers cited 75 times of the 15 papers. In addition, we also found 10 new granular papers according to our search criteria. Of these 55 papers, 30 of them are fuzzy related, 22 of them are rough related, 8 of them are application oriented. Some papers also discussed issues on data mining, neural networks, and decision support.

3.2 Research Issues of Granular Computing

Although there are appealing research results, granular computing research is still in it's early stage. It is suggested that the following research issues should be emphasized in future research in order to build up a healthier research theory and community.

Foundations and Basic Definitions The concept of granular computing has been loosely conveyed by many researcher for many years. However, the basic principles have been studied in different disciplines. It is crucial to narrow down the definitions of granular computing. Granular computing research originated from fuzzy set theory and later was influenced by rough set theory. Therefore, its foundations and methodology are mainly fuzzy and rough related. The study of the foundations of granular computing has drawn the attention of researchers. For instance, Yao [29] provides an in-depth look at the history of granular computing and from which domains similar ideas exist. It is argued that granular computing studies should be focused on the philosophical, methodological, and computation perspectives. In fact, one should also emphasize the applicational perspectives.

Individual Methodology Lead by fuzzy and rough set theory, many individual techniques are studied under the umbrella of granular computing as well as other terms. Neural networks, fractal analysis, and quotient space theory are some example methods found in our survey [30].

Basic Concepts Granules are basic and key components of any granular computing technique. Identification, classification and comparison of granules based on different granular computing techniques may help us gain more understanding of human information processing. Relationships amongst granules together with granulation are some other important issues [24].

Connections with Other Disciplines As suggested in [25], the granular computing community has less interaction with other research communities other than fuzzy sets and rough sets. Interacting and communicating with other research communities is one of the key issues for promoting the research of granular computing. This is also part of the aims of the annual IEEE Granular Computing Conference.

Hybrid Methods Information processing is often complex. Therefore, adopting a single technology may not be sufficient. Combining two or more granular computing techniques may enhance our computational abilities for information processing.

We list some of possible research issues and directions on granular computing in this subsection. Many researchers share similar concerns. For instance, it is suggested in a recent paper [29] that granular computing research should be diverse, inter-disciplinary and human-centric. In addition, a balanced and a both-idea-and-result-appreciated approach should be addressed.

4 Recent Developments in Granular Computing

We will review and summarize some of the representative research on granular computing in this section.

4.1 Triarchic Theory: Building Foundations of Granular Computing

The triarchic theory [29] is a representative research on the foundations of granular computing. As we discussed in the previous section, defining granular computing is one of the important research tasks this community. Instead of simply defining what granular computing research is, Y.Y. Yao views the scope of granular computing from three perspectives, namely, the philosophical perspective, methodological perspective and computational perspective [29]. It is argued that with each perspective focusing on different aspects of granular structures, the three perspectives working together will provide a more general and complimentary view of granular computing.

The philosophical perspective concerns structured thinking. Granular computing combines analytical thinking for decomposing a whole into parts and synthetic thinking for integrating parts into a whole. It is important to consider the conscious effects in thinking with hierarchical structures when using granular computing [29]. Although we consider 1997 as the birth year of the research on granular computing, the concept and philosophy have been used by many other disciplines for decades [25].

The methodological perspective concerns structured problem solving. The techniques for effective human problem-solving, such as systematic approaches to finding a solution, effective problem definition principles, and practical heuristics and strategies to check solutions to a problem, builds major foundations to granular computing. Using the hierarchical structure as a method for level-wise problem solving and determining at which level a solution is effective are some of key principles [29].

Computational perspective concerns structured information processing. Granular computing also focuses on the application of its theory to knowledge-intensive systems. The representation and processes of a system are two things to consider. Representation of a system describes the granules and granular structures within the application domain.

The granulation and computation with granules within the domain are the system processes. Granulation involves the construction of granules, levels, and hierarchies. Computational processes explore the granular structures in an attempt to find a solution.

A recent Ph.D. dissertation by Keet attempts to answer some fundamental issues for using granularity to improve knowledge representation and management [8]. It develops a formal, domain-independent and implementation-independent theory of granularity that can be used for computational reasoning. In particular, foundational semantics of granularity is disambiguated and structured in a taxonomy of types of granularity.

4.2 Human-Centered Information Processing

Human-centered information processing was initiated with the introduction of fuzzy sets. The insights have led to the development of the granular computing paradigm [1, 31]. Shifting from machine-centered approaches to human-centered approaches is considered one of trends in granular computing research [29].

Bargiela and Pedrycz's research adopt granular computing into a structured combination of algorithmic and non-algorithmic information processing that mimics human, intelligent synthesis of knowledge from information [1]. By integrating various different agents in which each pursues its own agenda, exploits its environment, develops its own problem solving strategy and establishes required communication strategies, one may form a more effective human-centered information system [15]. In fact, each agent may encounter a diversity of problem-solving approaches and realize their processing at the level of information granules that is the most suitable from their local points of view. To this level, the hybrid model raises a fundamental issue of forming effective interaction linkages between the agents so that they fully broadcast their findings and benefit from interacting with others [15].

In recent years, multi-agent systems have emerged as one of the interesting architectures facilitating distributed collaboration and distributed problem solving. Each node (agent) of the network might pursue its own agenda, exploit its environment, develop its own problem solving strategy and establish required communication strategies. Within each node of the network, one could encounter a diversity of problem-solving approaches. Quite commonly, the agents can realize their processing at the level of information granules that is the most suitable from their local points of view. Information granules can come at various levels of granularity. Each agent could exploit a certain formalism of information granulation engaging a machinery of fuzzy sets, interval analysis, rough sets, just to name a few dominant technologies of granular computing. Having this in mind, this raised another fundamental issue of forming effective interaction linkages between the agents so that they fully broadcast their findings and benefit from interacting with others [15].

4.3 Rough-Granular Computing

As we can see, rough set theory plays an important role in granular computing. A recent work by Skowron studies formation of granules with different criteria from a rough computing point of view [18]. When searching for optimal solutions satisfying some constraints, one of the challenges is that these constraints are often vague and imprecise. In addition, specifications of concepts and dependencies between them involving the in the constraints are often incomplete. Granules are constructed in computations aiming at solving such optimization tasks. General optimization criterion based on the minimal length principle was used. In searching for (sub-)optimal solutions, it is necessary to construct many compound granules using some specific operations such as generalization, specification or fusion. It is suggested that these criteria can be based on the minimal length principle, can express acceptable risk degrees of granules, or can use some utility functions [18].

Another interesting work is by using the rough-granular approach for the approximation of perceived concepts from sensory data and domain knowledge [7]. In this work, additional knowledge, represented by an ontology of concepts, is used to make it feasible to search for condition attributes relevant for the approximation of concepts on different levels of the concept hierarchy defined by a given ontology. It is argued that how ontologies of concepts can be discovered from sensory data remains one of the greatest challenges for many interdisciplinary projects on learning of concepts [7].

4.4 Dominance-based Rough Set Approach

The dominance-based rough set approach is another representation of rough set-based granular computing methodology. This approach extends the classical rough set approach by utilizing background knowledge about ordinal evaluations of objects and about monotonic relationships between these evaluations [19]. The indiscernibility or tolerance relation among objects, which is used in the classical rough set approach, has been replaced by the dominance relation: the only relation uncontested in multiattribute pairwise comparisons when attribute scales are ordered [19]. In addition, the fuzzy-rough approximations taking into account monotonic relationships between memberships to different sets may be applied to case-based reasoning [21].

4.5 Other Important Research Directions

Another influential paper is regarding a topological view of granular computing authored by Zhu [33]. It has received 9 citations. It ranked 18 for all papers with citation count greater or equal to 9. Zhu's paper studies covering-based rough sets from the topological view [33]. It uses topological methods to study a class of rough sets based on coverings.

Yager [23] adopts granular computing on information fusion applications. In particular, fuzzy sets are used to provide a granular representation of uncertain information about a variable of interest. However, in many cases when one makes some alteration of the information that is not completely valid one must weigh the tradeoff between the benefit gained from the alteration and the risk resulting from the lack of soundness of the alteration. In order to do this one must have some measure of validity or soundness of an alteration of our knowledge. In this paper, a measure of the soundness of replacing one fuzzy subset by another is proposed [23].

Zhang & Zhang proposed a theoretical framework of a fuzzy reasoning model under quotient space structure [32]. The quotient space structure is introduced into fuzzy sets to construct fuzzy set representations of different grain-size spaces and their relationships. The framework is aimed to combine two powerful abilities in order to enhance the efficiency of fuzzy reasoning: one is the ability of computing with words based on fuzzy set methodology, the other is the ability of hierarchical problem solving based on the quotient space approach. It is argued that the quotient space model enables us to implement a multi-granular analysis and thus a great benefit from the analysis can be achieved [32].

Liu studies granular computing from a rough logic aspect [9]. The granulation is based on the meaning of a rough logical formula in a given information system. Relative properties of the granulations, deductive reasoning of the granulations and λ-granular resolution strategies are studied. It is suggested that the practicability of the granulations will offer a new idea for studying the meaning of classical logic and the meaning of other nonstandard logic.

5 Concluding Remarks

To continue the study of "A ten-year review of granular computing [25]" published in 2007, this paper examines the most influential papers in granular computing. Based on the analysis of the impact papers, a list of key issues and tasks of granular computing research is given. In order to broaden and deepen the study of granular computing, one may focus on its foundations and definitions. Important issues, such as the formalization and understanding of granules, granulation, and granular relationships of various granular computing techniques should be emphasized. Applying individual techniques for real applications are essential, while hybrid systems should not be overlooked. Communicating with other disciplines and adopting non-traditional techniques to granular computing research will broaden, enhance, and solidate granular computing research.

We also summarize some recent developments of research in granular computing in this paper. It is hoped that one may gain more understanding of the current status and development of granular computing.

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