The Rise of Granular Computing

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Abstract:　 This paper has two purposes.　 One is to present a critical examination of the rise of granular computing and the other is to suggest a triarchic theory of granular computing.　 By examining the reasons, justifications, and motivations for the rise of granular computing, we may be able to fully appreciate its scope, goal and potential values. The results enable us to formulate a triarchic theory in the light of research results from many disciplines.　 The three components of the theory are labeled as the philosophy, the methodology, and the computation.　 The integration of the three offers a unified view of granular computing as a way of structured thinking, a method of structured problem solving, and a paradigm of structured information processing, focusing on hierarchical granular structures.　 The triarchic theory is an important effort in synthesizing the various theories and models of granular computing.

Key words: Triarchic theory of granular computing; systems theory; structured thinking, problem solving and information processing.

0.　Introduction

　　Although granular computing, as a separate field of study, started a decade ago [1], its basic philosophy, ideas, principles, methodologies, theories and tools has, in fact, long been used either explicitly or implicitly across many branches of natural and social sciences [2-7]. This observation immediately raises a number of fundamental questions. What are the unique features of granular computing that make us separate it as a new field of study? What is the role of granular computing in the context sciences in general and computer science in particular? What are the goals and scope of granular computing? What are the basic ingredients of a theory of granular computing? How can we provide a steady diet of fresh ideas and results to ensure that granular computing grows from a newborn into a mature scientific field of study?

　　The answers, at least partial answers, to these questions may be obtained by drawing and synthesizing results from well-established disciplines, including philosophy, psychology, neuroscience, cognitive science, education, artificial intelligence, computer programming, and many more.　 Previously, I argued that granular computing represents an idea converged from many branches of natural and social sciences [8-13].　 The idea may be simply described by the phrase *human-inspired computing and information processing with multiple levels of granularity*.　 In this paper, I will explore the rise of granular computing from two different angles in order to show that the idea of granular computing may have the power to overcome many of today's seemingly overwhelming challenges.　 I will explain the rise of granular computing by examining a challenge of artificial intelligence research and comparing it with the rise of systems theory a few decades earlier.　 The results help us to see the motivations, goals and scope of granular computing, and to fully appreciate the significance of the paradigm shift being brought on by granular computing.　 Finally, I will present a triarchic theory of granular computing and point out evidence that supports this theory.

1.　Human-Inspired Computing

　　Research on understanding the human brain and natural intelligence is closely related to the field of artificial intelligence (AI) and information technology (IT).　 The results have led to a computational view for explaining how the mind works [14].　 However, a major challenge faced by artificial intelligence researchers may be described by the Moravec's paradox [15] or Minsky's observation that "easy things are hard" [16], which was articulated more than 20 years ago and is still applicable today.　 An insightful finding by early artificial intelligence researchers is the dichotomy between machines and humans regarding the complexity or easiness in solving different problems. That is,

contrary to what researchers first assumed and believed, machines can do well things that humans find hard, and perform poorly on what is seemingly effortless for humans. Moravec [15] writes, "it is comparatively easy to make computers exhibit adult-level performance in solving problems on intelligence tests or playing checkers, and difficult or impossible to give them the skills of a one-year-old when it comes to perception and mobility." Minsky [16] raises an insightful question, "… if thinking is so complicated, what makes it seem so simple?" He further suggests, "… we cannot trust our offhand judgments about which of the things we do are simple, and which require complicated machinery."

A plausible explanation for the Moravec's paradox is based on the theory of evolution [15]. The human brain and all human skills are results of Darwinian evolution and they are implemented biologically. This natural selection process gradually and continually improves and optimizes such biological designs and implementations. Older skills, such as recognizing faces, recognizing voices, moving around in space, etc., are fully evolved and mastered by humans. We can perform these perception-based tasks almost unconsciously and they therefore appear to us to be effortless. For the same reason, reengineering the working principles underlying the human brain and older human skills are much more difficult. Consequently, we do not have satisfactory success in duplicating them in computers yet. In contrast, abstract thought is a new trick developed more recently in human evolutionary history and we have not fully mastered it yet. It therefore seems intrinsically difficult when we do it, as we must follow some precisely defined and constructed procedures. Such skills may not necessarily be difficult to reengineer and thus machines may easily duplicate them.

Moravec [15] suggests that this dichotomy provides "a giant clue to the problem of how to construct an intelligent machine." As a prerequisite, we need to reengineer the working principles of human intelligence before incorporating them into the design of intelligent systems [14, 17]. Researchers in several fields, including psychology, cognitive sciences, neuroscience, and artificial intelligence, attempt to build a computational theory for modeling and interpreting human intelligence [14, 18]. With the introduction of new instruments such as fMIR to probe the brain, there is a renewed surge of interest and urgency in understanding the brain, mind, and human intelligence among academics and practitioners.

In his 2002 AAAI presidential address, Mitchell [19] envisions AI research in the next ten years. He claims, "The synergy between AI and Brain Sciences will yield profound advances in our understanding of intelligence over the coming decade, fundamentally changing the nature of our field." In their white paper on a research map for explaining human intelligence, Berwick *et al.* [20] write, "We expect that developing a full understanding of the components of human intelligence could prove to be one of those great intellectual challenges that take 100 years to meet, so we should be half way there in time. … recently developed ideas and experimental methods—conceived and developed by visionary people in artificial intelligence, cognitive science, linguistics, systems neuroscience, and molecular neuroscience—fuel optimism for what can be done during the next ten years."

In their introductory paper of an edited book entitled "*Web Intelligence Meets Brain Informatics,*" Zhong *et al.* [21] lay out a new brain informatics perspective of Web Intelligence. Brain informatics is "a new interdisciplinary field that systematically studies the mechanisms of human information processing from both the macro and micro viewpoints by combining experimental cognitive neuroscience with advanced information technology. BI studies human brain from the viewpoint of informatics (i.e., human brain is an information processing system) and uses informatics (i.e., WI centric information technology) to support brain science study." In the introduction of an edited book entitled "*Cognitive Systems: Information Processing Meets Brain Science,*" Taylor [22] argues that it is the time for the conjunction of brain science and information technology. He writes, "First, there was the recognition of the importance of cognition and the fact that new tools are helping us to study living systems. Secondly, we would see that in some areas artificial cognitive systems are hitting a wall using a strictly engineering approach to problem solving."

In his book entitled "*How the Mind Works,*" Pinker [14] presents a cohesive picture of the mind by weaving the ideas from the computational theory of the mind and the theory of the natural selection of replicators. This framework may have a significant implication to the design of intelligent machine. In his book entitled "*On Intelligence,*" Hawkins [23] outlines a memory-prediction framework for explaining "real intelligence" in contrast to "artificial intelligence." This is driven by desires "not only to understand what intelligence is and how the brain works, but also to build machines that works the same way."

In his book entitled "*The Singularity is Near,*" Kurzweil [17] describes an "impending merger of our biological thinking with the nonbiological intelligence we are creating." He writes, "Understanding of the methods of the human brain will help us to design similar biologically inspired machine. Another important application will be to actually interface our brains with computers, … "

Wang [24] makes a great effort to introduce a new area of research called cognitive informatics. As defined by Wang, "*Cognitive Informatics* (CI) is a transdisciplinary enquiry of cognitive and information sciences that investigates the internal information processing mechanisms and processes of the brain and natural intelligence, and their engineering applications via an interdisciplinary approach."

Fundamental assumptions common to those studies are that "brains and computers embody intelligence for some of the same reasons" and there exists a set of common principles that underlies both human intelligence and artificial intelligence [14]. Although intelligent machines may be physically implemented different from brains, an understanding of the working principles of the brain is a prerequisite and indispensable for designing intelligent machines. Therefore, we need to have a unified framework of cognitive systems, including both natural and artificial systems, to investigate computing and information processing that are responsible for perception, thinking, learning, reasoning, communication, action, evolution and more [25].

A theory of human intelligence must contain explanations at multiple levels. One may study the brain by focusing on neurons and cortex regions with respect to their functions, organization and interactions. It is hoped that the results from a study of the brain directly will bring us insights to an in-depth understanding of human intelligence. For example, the memory-prediction model proposed by Hawkins [23] is based on a hierarchical organization of the cortex, which is backed up by evidence from neuroscience. The success of such a reverse-engineering approach depends on some pre-assumptions. As pointed out by Pinker [14], "Reverse-engineering is possible only when one has a hint of what the device was designed to accomplish." Alternatively, one may study human intelligence and the mind at conceptual and functional levels. An excellent example is the beautiful and simple model suggested by Minsky [26].

Minsky's model portrays a typical brain as containing a great many different parts called "resources." The concept of "resources" is used as an abstract notion without a direct linkage to biological implementation in a brain. A state of mind is explained from the activities of a certain collection of mental resources. According to Minsky [26], "Each of our major 'emotional states' results from turning certain resources on while turning certain others off – and thus changing some ways that our brains behave." "Each of our major Ways to Think results from turning certain resources on while turning certain others off – and thus changing some ways our brains behave." This amazingly simple model enables us to explain much more, including consciousness, levels of mental activities, common sense, and thinking. A six-level model of the mind, consisting of instinctive reactions, learned reactions, deliberative thinking, reflective thinking, self-reflective thinking, self-conscious reflection, is proposed.

Another conceptual model of the mind has been suggested in evolutionary psychology [27]. In particular, the mind is viewed as a set of special purpose thinking devices or computational modules. The massively modular architecture may be viewed as the result of natural selection; each module is adaptively tailored to solve a particular problem confronted by our ancestors. Although an analogy between organs and modules is commonly used, the detailed working principles of those modules at the neuron level are hardly discussed.

Many researchers are extremely optimistic about human intelligence prospects in the near future based on studying the human brain directly. Following Kuhn's model of the structure of scientific revolution [28], Mitchell [19] argues that new instrumentation, individual neuron recordings and brain imaging enables scientific revolutions in brain science and artificial intelligence. Winston [18] states, "I believe that we can discover the computational basis of natural intelligence during the next ten years or so." Kurzweil [17] suggests that we are much closer to an understanding of the brain that allows us to interface brains and computers.

If we truly understand the implications of the paradox, "easy things are difficult," we should perhaps appreciate the difficulty of reengineering brains based solely on recently available instruments. Building conceptual models of human-inspired computing and information processing is an important and complementary task in achieving the goal of unlocking the brain. This is where, I believe, granular computing will contribute. I will present a detailed argument in the next section.

2. **The Rise of Granular Computing**

A fundamentally important point, raised by Minsky [26], about human intelligence is that humans have many "Ways to Think" and can also create new "Ways to Think." According to Minsky, "If you 'understand' something in only one way, then you scarcely understand it at all – because when you get stuck, you'll have nowhere to go. But if you represent something in several ways, then when you get frustrated enough, you can switch among different points of view, until you find one that works for you!" If we want to understand natural intelligence, we need to build

models for explaining human "Ways to Think." Granular computing seems to focus on a particular class of such "Ways to Think."

Many authors, including myself, try to explain the rise of granular computing from several different points of view. Based on the discussions of the last section, it becomes evident that granular computing may well serve the needs for an understanding of human intelligence. In particular, granular computing concerns a theory and a conceptual model of human-inspired computing and information processing, as well as their applications in problem solving. We first look at some arguments from a set of landmark papers in three important contributing areas to granular computing, namely, artificial intelligence, fuzzy sets and rough sets.

In artificial intelligence, Hobbs [29] proposes a theory of granularity that has influenced several later studies, including hierarchical planning [30] and quotient space theory [31]. He gives the motivations of the theory as follows. "We look at the world under various grain sizes and abstract from it only those things that serve our present interests." "Our ability to conceptualize the world at different granularities and to switch among these granularities is fundamental to our intelligence and flexibility. It enables us to map the complexities of the world around us into simple theories that are computationally tractable to reason in. If we are to have a machine of even moderate intelligence, it must have a theory of granularity woven into the very foundation of its reasoning processes."

In fuzzy set theory, Zadeh [7] suggests the notion of fuzzy information granulation. In his 1997 seminal paper on granular computing, Zadeh gives several motivations. In particular, he writes, "Among the basic concepts which underlie human cognition there are three that stand out in importance. The three are: granulation, organization and causation. In a broad sense, granulation involves decomposition of whole into parts; organization involves integration of parts into whole; and causation relates to association of causes with effects." The view of granular computing as human-inspired computing is explicitly stated. According to Zadeh, "Inspired by the ways in which humans granulate human concepts – we can proceed to granulate conceptual structures in various fields of science." More specifically, "… fuzzy information granulation in an intuitive form underlies the human solution." Bargiela and Pedrycz [32] further articulated this view in their book and papers. In a recent paper, they state, "The insights that were afforded through this formalism [human-centred information processing] have led to the development of the Granular Computing paradigm in the late '90s. Subsequent research has highlighted the fact that many founding principles of Granular Computing have in fact been adopted in other information processing paradigms and indeed in the context of various scientific methodologies." They suggest that granular computing may be viewed as "a structured combination of algorithmic and nonalgorithmic information processing that mimics human, intelligent synthesis of knowledge from information."

In rough set theory, Pawlak [33] emphasizes the importance of knowledge granulation and its relation to the philosophy of rough sets. He writes, "Granularity of knowledge, information, measurements, computations etc. seems to be an intrinsic feature of our thinking and can be considered as a manifestation of an old antinomy associated with *continuo[u]s-discrete* paradigm." "Granularity is inherently connected with foundation of rough set theory." Polkowski and Semeniuk-Polkowska [34] point out that "[g]ranulation of knowledge is one of important aspects of the way in which the human brain works" and such studies have at least two purposes. "First, to get an insight into the processes of perception, concept formation, and reasoning in the brain; second, to transfer this knowledge into the realm of applications." To some extent, the rise of granular computing is due to the solid formulation and successful application of the rough set theory [33-45].

Once we accept the idea that granular computing is human-inspired computing, information processing and problem solving, we need to develop its concrete details. In a wider context, it may be viewed as nature-inspired computing [46]. This requires watching humans at work. In my previous papers [8-13], based on evidence from many disciplines, I argue that people solve different problems by using some common principles. Granular computing focuses on a particular class of those principles characterized by the use of multiple levels of granularity, namely, levels of organization, levels of control, levels of complexity, levels of understanding, levels of description, levels of representation, levels of interpretation, levels of abstraction, levels of details, levels of processing and so on. Unfortunately, these principles are scattered over many places in isolation without being synthesized into an integrated whole. They are normally explained with reference to discipline-specific knowledge and thus are buried deeply in minute details. Typically, the same principles are discussed in different languages and notations. In many occasions, we use these principles either implicitly or subconsciously, for a formal documentation does not exist. This has led to the reinvention of the same principles time and again in the same or different fields. By introducing granular computing as a new field of study, we attempt to resolve such problems.

Granular computing embraces human-oriented and machine-oriented approaches by discovering principles that

underlie natural and artificial cognitive systems. With the human-oriented perspective, one task of granular computing is to extract high-level commonalities of different disciplines and to synthesize their results into an integrated whole by ignoring low-level details; the other is to make explicit ideas hidden in discipline-specific discussions in order to arrive at a set of discipline-independent principles. Specifically, we want to achieve the following goals: a) to make implicit principles explicit, b) to make invisible principles visible, c) to make domain-specific principles domain-independent, and d) to make subconscious effects conscious [13]. Through such efforts, it is hoped that the philosophy and methodology of granular computing will empower more people with effective strategies for problem solving tasks. More importantly, one can consciously apply the principles of granular computing in solving a wide range of problems. With the machine-oriented perspective, we want to design human-inspired machines and systems that fully explore a mode of computing and information processing with multiple levels of granularity. That is, what links the two perspectives is the dependency of machine-oriented approaches on human-oriented approaches. A machine-oriented approach is possible only if we have an in-depth understanding of the human-oriented counterpart.

This setting enables us to compare the rise of granular computing and the rise of the general systems theory several decades earlier. The general systems theory attempts to discover and investigate structures and underlying principles common to most natural and artificial systems [47-50]. Some authors view the study of the general systems theory as building a science of sciences and an attempt to arrive at unity through diversity [47, 48]. Similarly, research of granular computing attempts to derive a unified framework for human-inspired computing, with applications to both human and machine computing and problem solving. The scope and goals of granular computing are broad and bold. Some authors suggest that granular computing may bring a paradigm shift in computing [2]. In this regard, I would like to draw the attention to a well-cited earlier criticism by Lilienfeld [49, 51] about systems theory: "Systems thinkers exhibit a fascination for definitions, conceptualizations, and programmatic statements of a vaguely benevolent, vaguely moralizing nature … They collect analogies between the phenomena of one field and those of another … the description of which seems to offer them an esthetic delight that is its own justification … no evidence that systems theory has been used to achieve the solution of any substantive problem in any field whatsoever has appeared." This criticism may be equally applicable to some current research in granular computing. Therefore, we must show that granular computing does offer something new and make a solid and concrete contribution to science in general and computer science in particular, instead of a restatement of existing results by using a different language or notions.

It may be fair to say that granular computing is both old and new. Granular computing is old in the sense that its basic ideas, principles, strategies, methodologies, and tools have indeed appeared and reappeared in many branches of science and various fields of computer science under different names and with different notations. It is new by its distinctive goals and agenda. Based on the existing studies, granular computing is growing into a school of thought and a full-scale theory, focusing on problem solving and information processing in the abstract, in the brain, and in machines. Granular computing may be viewed as an interdisciplinary study of computations in nature, society, and science, as well as abstract models of such computations, with an underlying notion of multiple levels of granularity. It extracts and studies principles, strategies, and heuristics common to all types of problem solving and information processing.

At the same time, we need to be more realistic about granular computing research, with more concrete and feasible short-term goals and achievements, in order to avoid future disappointments. By restricting to a particular class of methods or ways to think, granular computing would lead to new computational models that may help us to understand a specific aspect of natural intelligence and to apply it when designing cognitive machines. In other words, the study of granular computing should focus on one aspect of problem solving characterized by multiple levels of granularity, instead of investigating all aspects. Granular computing will contribute to the repertoire of "Ways to Think." This perhaps makes granular computing more appealing and its research goals feasible.

3. The Triarchic Theory of Granular Computing

The discussions of the last two sections provide a context for studying granular computing. The triarchic theory is a unified view that stresses the study of granular computing as a new field in its wholeness, rather than scattered pieces. Based on multiple level hierarchical structures, the triarchic theory integrates philosophical, methodological, and computational issues of granular computing as structured thinking, structured problem solving and structured information processing, respectively. A brief description of the theory is given in this section and more details can be found in [11-13].

3.1 Multilevel and Multiview Hierarchical Granular Structures

When building a theory for modeling structured thinking, structured problem solving, and structured information processing, the first challenge is to choose a simple and yet flexible class of granular structures. Many different structures have been proposed and used, for example, partitions and coverings of a universal set in a set-theoretic setting. The choices of different structures may lead to many research directions.

It seems that hierarchical granular structures is a good candidate for developing a theory of granular computing. By a *hierarchical structure* (i.e., *hierarchy*), I mean a loosely defined structure that is weaker than a tree or a lattice. The basic ingredients of a granular structure are a family of granules, a family of levels, and partial orderings on granules and levels. Granules are used as an abstract and primitive notion whose physical meaning becomes clearer only when a particular application or concrete problem is considered. Intuitively speaking, granules are parts of a whole. They are the focal points of our current interest or the units we used to obtain a description or a representation. For example, with respect to Minski's model of the mind, "resources" may be interpreted as granules. Similarly, in a massively modular architecture of evolutionary psychology, "modules" may be interpreted as granules.

A granule serves dual roles: it is a single undividable unit when it is considered as a part of another granule; it is a whole consisting of interconnected and interacting granules when some other granules are viewed as its parts. We need to characterize granules by a minimum set of three types of properties. The internal properties of a granule reflect its organizational structures and the relationships and interaction of its element granules. The external properties of a granule reveal its interaction with other granules. The contextual properties of a granule show its relative existence in a particular environment. The three types of properties together provide us a full understanding of the notion of granules.

We may collect a family of granules of a similar type together and study their collective properties. This leads to the notion of levels. While each granule provides a local view, a level provides a global view. An important property of granules and levels is their granularity, which enables us to order partially granules and levels. Such an ordering results in a hierarchical view. In building a hierarchical structure, we explore a vertical separation of levels and a horizontal separation of granules at the same hierarchical level [52]. Usually, the two separations must ignore information that is irrelevant to the current interest or does not greatly affect our solution. Furthermore, a single hierarchy only represents one view. By considering multiple hierarchies, we obtain a multiview framework [53]. The granular structures studied in granular computing may be more accurately described as a multilevel view given by a single hierarchy and a multiview understanding given by many hierarchies.

3.2 The Granular Computing Triangle

The core of the triarchic theory can be simply described by the granular computing triangle. The three vertices of the triangle represent the philosophical, methodological and computational perspectives.

Philosophy: The philosophy of granular computing offers a worldview characterized by different sized, interacting and hierarchically organized granules. This view of the world in terms of structures as represented by multiple levels leads to a way of structured thinking, which is applicable to many branches of natural and social sciences. In fact, multilevel structures have been widely used, including levels of abstraction in almost every branch of sciences, levels of understanding in education, levels of interpretation in history and language understanding, levels of organization in ecology and social sciences, levels of complexity in computer science and systems theory, levels of processing in modeling human memory, levels of details in programming languages, and many others.

Broadly speaking, granular computing draws results from two complementary philosophical views about the complexity of real-world problems, namely, the traditional reductionist thinking and the more recent systems thinking. It combines analytical thinking for decomposing a whole into parts and synthetic thinking for integrating parts into a whole.

Methodology: As a general method of structured problem solving, granular computing promotes systematic approaches, effective principles, and practical heuristics and strategies that have been used effectively by humans for solving real-world problems. A central issue is the exploration of granular structures. This involves three basic

tasks: constructing granular structures, working within a particular level of the structure, and switching between levels. We can formulate a set of principles to highlight the methodology of granular computing.

Several such principles are considered here. The principle of *multilevel granularity* emphasizes the effective use of a hierarchical structure. According to this principle, we must consider multiple representations at different levels of granularity. The principle of *multiview* stresses the consideration of diversity in modeling. We need to look at the same problem from many angles and perspectives. Once granular structures are obtained, we can apply other principles to work based on such structures. For example, the principle of *focused efforts* calls for attention on the focal point at a particular stage of problem solving; the principle of *granularity conversion* links the different stages in this process. The principle of *view switching* allows us to change views and to compare different views. Those principles of granular computing have, in fact, been used extensively in different disciplines under different names and notation. Many principles of structured programming can be readily adopted for granular computing.

Computation: As a new paradigm of structured information processing, granular computing focuses on computing methods based on the granular structures. The term computing needs to be understood in its broad meaning to include information processing in the abstract, in the brain and in machines. While information processing in the abstract deals with theories of computing without direct reference to their implementations, information processing in the brain and in machines represent the biological (natural) and the physical (artificial) implementations, respectively.

Two related basic issues of computation are representations and processes (operations). Representation covers the formal and precise description of granules and granular structures. Processes may be broadly divided into the two classes: granulation and computation with granules. Granulation processes involve the construction of the building blocks and structures, namely, granules, levels, and hierarchies. Computation processes explore the granular structures. This involves two-way communications up and down in a hierarchy, as well as switching between levels.

The three perspectives of granular computing are connected and mutually support each other. Their integration puts granular computing research on a firm basis. In addition, the granular computing triangle recommends a research direction towards an interdisciplinary wholeness approach. That is, researchers in different disciplines may investigate different perspectives of granular computing and at the same time integrate their individual results.

4. Concluding Remarks

According to the working principle of granular computing, to completely learn and understand an area of study, we must achieve it at multiple levels. At a concrete level, we must understand all its definitions, formulations and theories. At a higher level, we must understand and be able to classify its main schools of thought, representative points-of-view, major sub-areas, and landmark achievements. For a much higher-level appreciation, we need to put the area of study in the general context of other areas of study. That is, we need to examine the unique features and contributions of the particular area of study in relation to other areas, to understand the motivations and driving forces that influence its evolution, and to probe and predict its future. In this paper, I made an attempt to achieve the last one.

Granular computing is an interdisciplinary and a multidisciplinary study, emerging from many branches of natural and social sciences. Results from cognitive science and psychology on human guessing, knowing, thinking and languages provide evidence to support the philosophical view of granular computing that humans perceive, understand, and represent the real world in multiple levels of granularity and abstraction. Results from the general systems theory, regarding efficient evolution of complex systems and organized complexity, suggest that multilevel hierarchical granular structures used in granular computing are suitable for describing complex real-world problems. The effective methodology of structured programming, characterized by top-down design and step-wise refinement, is generally applicable to other types of problem solving, and hence may provide a methodological foundation for granular computing. The systematic study of human problem solving, strategies and heuristics, knowledge representation and search, in artificial intelligence may provide the necessary models, methods, and tools required by granular computing. Advances in information processing and related systems may help in establishing a computational basis of granular computing. The Triarchic Theory of granular computing reflects the above integration. It consists of the philosophy, methodology, and computation perspectives based on multilevel and multiview hierarchical granular structures. While a single hierarchy offers one representation and understanding with many levels of granularity, multiple hierarchies afford a complete understanding from many views.

Regarding future research on granular computing, I would like to reiterate a few comments. First, we need to emphasize a balanced approach by considering all three perspectives. Second, we stress the need for diversity in order to arrive at a unity. Third, we need to cross the boundaries of different disciplines, in order to observe their commonalities and to use them for granular computing. Fourth, we need to shift from machine-centric approaches to human-centric approaches. Fifth, we need to move beyond the current rough sets and fuzzy sets dominated research agenda in order to put granular computing in its wider perspective. Finally, we need to learn to appreciate both the power of ideas and value of concrete results.

5. Acknowledgements

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