Human-Inspired Granular Computing

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Abstract: In this chapter, I explore a view of granular computing as a paradigm of human-inspired problem solving and information processing, covering human-oriented studies and machine-oriented studies. By exploring the notion of multiple levels of granularity, one can identify, examine and formalize a special family of principles, strategies, heuristics, and methods that are commonly used by humans in daily problem solving. The results may then be used for human and machine problem solving, as well as for implementing human-inspired approaches in machines and systems. The triarchic theory of granular computing unifies both types of studies from three perspectives, namely, a philosophy of structured thinking, a methodology of structured problem solving, and a computation paradigm of structured information processing. The stress on multilevel, hierarchical structures makes granular computing a human-inspired and structured approach to problem solving.

Keywords: Triarchic theory of granular computing, granular computing triangle, granular structures, multiview, multilevel, structured thinking, structured problem solving, structured information processing

1. Introduction

In two recent papers, J.T. Yao (2007, 2008) presents a ten-year review of granular computing by analyzing published papers collected from the ISI's *Web of Science* and the *IEEE Digital Library.* The objective is to "study the current status, the trends and the future direction of granular computing and identify prolific authors, impact authors, and the most impact papers in the past decade." The results from such a citation analysis shed new lights on the current research in granular computing. For example, it is found that the current research is dominated by fuzzy sets and rough sets, and the number of granular computing publications has a linear growth rate. According to a study by Crane (1972), this indicates that members of the granular computing community have less interaction with each other and with researchers in other areas. To promote granular computing as a field of study, J.T. Yao (2007) makes several recommendations. We must first search for and adopt a set of common terminologies and notations so that we can easily find granular computing papers and increase effective exchange of ideas. We need to interact and communicate with each other and with researchers in other fields.

An immediate task is to establish a conceptual framework of granular computing, within which many views, interpretations, and theories can be developed and examined. Although a well-accepted definition and formulation of granular computing does not exist yet, recent results show a great diversity of research and a convergence to a unified framework. Initiatives include granular computing as a way of problem solving (Yao, 2004a, 2004b, 2007a; Zhang and Zhang, 2007), granular computing as a paradigm of information processing (Bargiela and Pedrycz, 2002, 2008), artificial intelligence perspectives on granular computing (Yao, 2008b, Zhang and Zhang, 2007), connections between granular computing and systems theory (Yao, 2008b), a general theory of granularity (Hobbs, 1985; Keet, 2006, 2008), and a triarchic theory of granular computing (Yao, 2000, 2004a, 2004b, 2005, 2006, 2007a, 2008a, 2008b). Granular computing is evolving from a set of simple concepts and notions into a field of interdisciplinary and cross-disciplinary study. It draws results from many fields and synthesizes them into an integrated whole (Yao, 2007a, 2008b).

One purpose of this chapter is to examine a view of granular computing as a paradigm of human-inspired problem solving and information processing with multiple levels of granularity. I classify research of granular computing into human-oriented and machine-oriented studies, and discuss two purposes of granular computing, one for humans and the other for machines. Another purpose is to outline the triarchic theory of granular computing with three components integrated. The studies of philosophy of granular computing promote structured thinking, the studies of methodology promote structured problem solving, and the studies of computation promote structured information processing. The classification of the two types of studies and the identification of the two purposes help clarify some confusion about the goals and scopes of granular computing.

The view of granular computing as a paradigm of human-inspired computing with multiple levels of granularity is not really new; it simply weaves together powerful ideas from several fields, including human problem solving, computer programming, cognitive science, artificial intelligence, and many others. By revisiting, reinterpreting and combing these ideas, we obtain new insights into granular computing. In the rest of the chapter, I will explain this view with reference to works that have significant influences on my thinking; and hope this will help in appreciating the principles and ideas of granular computing.

2. Granular Computing as Human-inspired Problem Solving

Several important characteristics of human problem solving may be considered as a starting point for approaching granular computing. First, humans tend to organize and categorization is essential to mental life (Pinker, 1997). Results of such organizations are some types of structures. For example, hierarchical structures seem to be a reasonable choice. Second, humans tend to form multiple versions of the same world (Bateson, 1978) and to have several kinds of data presentations in the brain (Pinker, 1997). For a particular problem, we normally have several versions of descriptions and understanding (Minsky, 2007). Third, we consider a problem at multiple levels of granularity. This allows us to focus on solving a problem at the most appropriate level of granularity by ignoring unimportant and irrelevant details (Hobbs, 1985). Fourth, we can readily switch between levels of granularity at different stages of problem solving (Hobbs, 1985); we can also easily switch from one description to another. At the present stage, we may not be ready to define all these characteristics quantitatively. They may only be explained to humans qualitatively through a set of rules of thumb. With the efforts of granular computing researchers, we expect to formalize some or all of them.

Let us now consider three specific issues in the study of granular computing as human-inspired problem solving.

First, granular computing focus on a special class of approaches to problem solving; this classes is characterized by multiple levels of granularity. Regarding human intelligence, Minsky (2007) points out that humans have many "Ways to Think." We can easily switch among them and create new "Ways to Think" if none of them works. It is easy to convince us that humans have many approaches to problem solving. The use of multiple levels of granularity and abstraction is only one of them. It may be more realistic for the study of granular computing not to cover the whole spectrum of approaches to human problem solving. Therefore, I restrict study of granular computing to human-inspired and granularity-based way of problem solving.

Second, the study of granular computing has two goals. One is to understand the nature, the underlying principles and mechanisms of human problem solving, and the other is to apply them in the design and implementation of human-inspired machines and systems. They in turn lead to two classes of research on granular computing, namely human-oriented studies and machine-oriented studies. These two types of studies are relatively independent and mutually support each other. The former focuses on human problem solving and the latter on machine problem solving.

Third, the study of granular computing serves two purposes. On the one hand, an understanding of the underlying principles of human problem solving may help more people to consciously apply these principles. Once we articulate and master these principles, we become a better problem solver. I use the phrase "granular computing for humans" to denote this aspect. On the other hand, an understanding human problem solving is a prerequisite of building machines having the similar power. The human brain is perhaps the only device that represents the highest level of intelligence for problem solving. Unlocking the mechanisms of human brain may provide the necessary hints on designing intelligent machines. Results from human-oriented studies may serve as a solid basis for machine-oriented studies. Once we have a full understanding of human problem solving, we can design machines and systems based on the same principles. I use the phrase "granular computing for machines" to denote the second aspect. In summary, granular computing is for both humans and machines.

To conclude this section, I look at granular computing again in the light of a conceptual framework by Golhooly (1989) on problem solving. According to Gilhooly, there are three angles from which one may approach the topic of problems solving. The normative approaches deal with the best means for solving various types of problems; the psychological studies attempt to understand and analyze problem-solving processes in humans and other animals; computer science, or more specifically artificial intelligence, approaches focus on machine problem solving. The cognitive science integrate both human and machine problem solving from an information-processing point of view. It covers information and knowledge processing in the abstract, in human brains and in machines. Based on these results, Gilhooly suggests developing "a comparative cognitive science of problem solving in which the differing information-processing procedures followed by human and machine may be compared and contrasted, with a view to developing general principles applicable both to natural and artificial problem solving." It offers three perspectives on problem solving, namely, the psychological (or human) perspective, the machine perspective, and the interaction of human and machine perspectives. If we view granular computing as human-inspired problem solving, the comparative cognitive science framework is also instructive to the study of granular computing.

The interaction of human and machine perspectives consider bidirectional influences. Machine analogies contribute to psychological approaches to human thinking, which leads to the machine-inspired information-processing approach to the study of human intelligence. Conversely, human-inspired problem solving may contribute a great deal to machine problem solving. While research on the former is abundant, there is still a lack of study on the latter. Since human problem solving processes are rarely known in detail, and hence are not described in precise terms and in a formal way, we have only rather general influences from human problem solving to machine problem solving (Gilhooly, 1989). Granular computing attempts to fill this gap by focusing on human-inspired approaches to machine problem solving.

3. Human-oriented and Machine-oriented Studies

For human-oriented studies of granular computing, we focus on a particular way of human problem solving that uses multiple levels of granularity. We attempt to identify, extract and formalize such a class of principles, strategies, heuristics and methods. The main objective is to understand and unlock the underlying working principle of granular thinking, and to develop new theories and methods for human problem solving. On the evidence and results from human-oriented studies, the machine-oriented studies focus on the application of granular computing in the design and implementation of human-inspired machines and systems.

For machine-oriented studies of granular computing, we assume that the principles of human problem solving apply equally to machines. The principles of human problem solving may be applied either directed or indirectly to intelligent machines. It may be true that one can build special machines and systems for solving particular types of problem, independent of human problem solving. However, without an understanding of human problem solving, we cannot expect a high likelihood of building a general problem solving machine or system that has the human-level capacity. Machines may solve a problem in a different manner as humans; they must employ the same underlying principles.

Granular computing integrates human-oriented and machine-oriented studies, relying on the dependency of the latter on the former. Particularly, granular computing involves the following sequence of tasks:

(1) to understand the underlying principles and mechanisms of human problem

solving, with emphasis on multiple levels of granularity,

(2) to extract a set of principles of granular computing,

(3) to develop formal methodology, theories and models of granular computing,

(4) to empower everyone with principles of granular computing,

(5) to design human-inspired machines and systems for problem solving.

Therefore, the task (1) emphasizes the role of multiple levels of granularity and limits the scope of granular to a special class of approaches to problem solving. Results from (2) may be intuitive, qualitative, schematic, subjective, incomplete, philosophical, and/or relative vague; they are represented as heuristics, common-sense rules and/or rules of thumb and explained in natural languages. Results from (3) may be interpreted as the next level articulation and precision of the results from (2), and inevitably less general and more restrictive. Results from (2) and (3) may be directly applied to granular computing for humans, namely, task (4). While results from (3) can be directly applied to granular computing for machines, namely, task (5), results from (2) play only a guiding role.

A main stream of research of granular computing focuses on tasks (3) and (5), with very little attention to other tasks. This seems to be paradoxical. On the one hand, it is well recognized that granular computing is motivated by the ways in which humans solve problems (Yao, 2008b). On the other hand, we have not started a systematic and full-scale study of human problem solving in granular computing, although there are extensive studies in other fields such as cognitive science, psychology, education, and many more. We over emphasize granular computing for machines and fail to appreciate the power of granular computing for humans.

Some misunderstandings about granular computing may stem from a confusion of granular computing for humans and granular computing for machines. Many questions, doubts, and criticisms of granular computing are only applicable to (5), where formal, precise and concrete models are necessary. As granular computing for humans, namely, (4), its principles can be explained at more abstract levels and in an informal manner, relying heavily on human intuition, understanding and power. It may take times before we can have some breakthroughs in precisely defining all aspects of human problem solving. However, this should not discourage us to pursue.

The idea of separating and integrating human-oriented and machine-oriented studies is influenced by results and lessons from the fields of artificial intelligence (AI) and computer programming. Let us first consider artificial intelligence. Several decades ago, Samuel (1962) identified two fundamentally different approaches to artificial intelligence. One approach focuses the problem and not the device that solves it. That is, the specific mechanisms of the brain are not considered. The other approach focuses on the studies on devices that solve the problem and the emulation of such devices. Some researchers consider that building an intelligent machine is the primary goal of AI, and that finding out about the nature of intelligence is the second goal (Schank, 1987). Consequently, they have led to different approaches to artificial intelligence.

The earlier advances in AI, such as theorem proving, computer chess, and so on, depend crucially on a deep understanding of how humans solve the same problems

(Newell and Simon, 1972). Successful intelligent systems are built based on the same principles. However, a lack of consideration by AI researchers about the human mind and natural intelligence has perhaps negatively affected the development of artificial intelligence (Hawkins, 2004; Schank, 1987). In the last few years, many researchers began to reconsider the role of the studies of brain science and natural intelligence for artificial intelligence. A fully exploration on this account and many references can be found in another paper (Yao, 2008b). It seems that understanding the nature of intelligence is the primary goal of AI, which in turn supports the goal of building intelligent machines. In the context to granular computing, human-oriented studies should be considered as the primary focus.

The National Academy of Engineering (2008) lists "reverse-engineer the brain" as one of the 14 grand challenges for engineering for the 21st century. The following excerpt from its document supports the above argument:

> "While some of thinking machines have mastered specific narrow skills - playing chess, for instance - general-purpose artificial intelligence (AI) has remained elusive.
>
> Part of the problem, some experts now believe, is that artificial brains have been designed without much attention to real ones. Pioneers of artificial intelligence approached thinking the way that aeronautical engineers approached flying without much learning from birds. It has turned out, though, that the secrets about how living brains work may offer the best guide to engineering the artificial variety. Discovering those secrets by reverse-engineering the brain promises enormous opportunities for reproducing intelligence the way assembly lines spit out cars or computers.
>
> Figuring out how the brain works will offer rewards beyond building smarter computers. Advances gained from studying the brain may in return pay dividends for the brain itself. Understanding its methods will enable engineers to simulate its activities, leading to deeper insights about how and why the brain works and fails."

We may pose a similar challenge to granular computing. That is, a grand challenge for granular computing is to reverse-engineer the mechanisms of human problem solving. It is of significant value to both human and machine problem solving

Consider now the problem of computer programming. Programming is a complex and difficult problem solving task. Many methodologies and principles have been proposed and effectively applied. It is one of best examples that we may use to explain and articulate principles of human problem solving. It also supports the view of "granular computing for humans." Programming methodologies empower programmers rather than machines, namely, programming methodologies are for humans. Research on this angle of granular computing may be more fruitful at the present stage. In previous papers (Yao, 2004a, 2007a), I argue that the principles and methodologies of computer programming may be easily adopted for granular computing.

The division of granular computing for humans and for machines is also related to a programming paradigm known as the literate programming proposed by Knuth (1984). It represents a change of attitude: the task of programming is changed from instructing a computer what to do into explaining to human beings what we want a computer to do

(Knuth, 1984). A program in WEB, a system for literate programming, is the source for two different system routines: one to produce a document that describes the program clearly for human beings, and the other to produce a machine-executable program. The explanations of a program are a salient feature of literate programming. Borrowing the ideas of literate programming to granular computing, one may focus on explaining to human beings about human problem solving. Once we can explain the principles of human problem solving clearly, we may be able to design systems that adopt the same principles.

There are several benefits from separating human-oriented and machine-oriented studies and from separating granular computing for humans and for machines. First, they identify clearly the scopes and goals of granular computing. Second, they enable us to recognize the importance of granular computing for humans, an aspect that has been overlooked so far. Third, they make us to ask the right questions and to tackle the right problems with respect to different tasks of granular computing. Fourth, they help us to envision different stages of study on granular computing with both long-term and short-term perspectives.

4. Granular Computing for Humans

My previous effort concentrated on granular computing for humans (Yao, 2004a, 2005, 2007a). An assumption of such studies is that there is a set of common principles underlying human problem solving, independent of particular problem domains and specific problems. Consider, for example, scientific research that is a typical task of problem solving. Although scientists in different disciplines study different subject matters and use different formulations, they all employ remarkably common structures for describing problems and apply common principles, strategies, and heuristics for problem solving (Beveridge, 1967; Martella *et al.*, 1999). On the other hand, these common principles are examined in relative isolation, expressed in discipline dependent concepts and notions, buried in technical details, and scattered in many places. Granular computing aims at extracting the common discipline-independent principles, strategies and heuristics that have been applied either explicitly or implicitly in human problem.

I list the following specific goals about studying the principles of granular computing and their usages (Yao, 2007a):

- to make implicit principles explicit,
- to make invisible principles visible,
- to make discipline-specific principles discipline-independent,
- to make subconscious effects conscious.

The principles of granular computing serve as a guide in the problem solving process, and may not guarantee a good solution. However, by making these principles explicit, visible and disciplinary-independent to everyone, we increase the probability of arriving at a good solution. If we can precisely and clearly describe the principles of granular computing, we can empower more people to effectively use them in problem solving. There is evidence from psychology and cognitive sciences that shows the benefits from our awareness of these rules and our conscious effort in using them. For example, the conscious access hypothesis states, "consciousness might help to mobilize and integrate brain functions that are otherwise separate and independent" (Barrs, 2002). If we can change from subconscious behaviors into a systematic conscious effort in applying the principles of granular computing, it is more feasible that we become better problem solvers.

The central ideas of granular computing for humans derive from several studies in computer science. In the context of structured programming, Dijkstra (EWD237, EWD245) makes a compelling and beautiful argument that promotes a conscious effort at exploiting good structures as a useful thinking aid. Specifically, when one makes a conscious effort at using good structures and principles, it is more feasible to produce a correct program. Influenced by Dijkstra's ideas, I single out two crucial issues about granular computing for humans. One is the extraction of structures and principles of granular computing, and the other is to promote a conscious effort in using these principles.

In the context of computer education, Wing (2006) points out the importance of computational thinking, in addition to the classical three Rs (reading, writing, and arithmetic). She argues that computational thinking represents a universally applicable attitude and skill set that can be learned and used by everyone, not just computer scientists. In some sense, it represents a view of computational thinking for humans. For this reason, I choose the phrase "granular computing for humans," with an understanding that granular computing has a large overlap with computational thinking.

Dijkstra attempts to convince programmers to make a conscious effort in using good structures and principles of structured programming, and Wing attempts to make computational thinking, originally developed in computer science, as a universally applicable attitude and skill set to everyone. In several papers (Yao, 2004a, 2005, 2007a), I suggest that some of the basic principles of computer programming and computational thinking, such as top-down design, step-wise refinement, multiple levels of abstraction, and so on, are some of the important ingredients of the methodology of granular computing. Granular computing for humans is therefore aims at a methodology applicable to many fields and to everyone.

There is evidence supporting the viewpoint of granular computing for everyone. Leron (1983) and Friske (1985) demonstrate that the principles of structured programming are equally applicable in developing, teaching and communicating mathematical proofs. Recently, several authors (Han and Dong, 2007; Xie et al., 2008; Zhu, 2008) apply ideas of granular computing to software engineering and system modeling. In another paper (Yao, 2007b), I argue that scientists may employ the principles of granular computing in structured scientific writing. Some authors (Sternberg and Frensch, 1991) show that principles of granular computing have, in fact, been used in reading, writing, arithmetic, and a wide range of tasks. It may be the time to study granular thinking as an effective and applicable methodology for humans.

5. Granular Computing for Machines

Granular computing for machines deals with more specific and concrete theories and methods. Central issues are to represent information and knowledge at multiple levels of granularity, to process it based on such a multilevel granular structure, to reasoning at multiple levels of abstraction, and to explore variable levels of schematic and approximate solutions of problems, from qualitative and symbolic to quantitative and numeric. Depending on particular applications, the high-level principles of granular computing may be implemented differently.

The major research effort on granular computing for machines focuses on an information processing perspective (Bargiela and Pedrycz, 2002, 2008; Lin *et al.*, 2002; Pedrycz, et al., 2008; Yao, 2007a). Three areas related to granular compting are the rough set model (Pawlak, 1998), the fuzzy set model (Zadeh, 1997), and artificial intelligence. The notion of information and knowledge granulation plays an essential role. Rough set theory studies a particular type of granulation known as partitions. Each block of a partition is called a granule. The multilevel granular structure is the lattice formed by all equivalence classes and unions of equivalence classes (Yao, 2004a). Normally, such a structure is defined based on different subsets of attributes in an information table. The model thus provides an effective means for analyzing information tables based on various granulations. In fuzzy set theory, a granule is interpreted as a fuzzy set that quantitatively defines a natural language word. It provides a framework of computing with words and approximate reasoning with granules. Artificial intelligence studies knowledge representation, abstraction, reasoning, learning, problem solving, and many more topics. The notions of granularity and abstraction have been investigated many authors (Yao, 2008a). The results from these fields, though limited, establish groundwork of granular computing.

Instead of giving a full account of granular computing for machines, I will address a few fundamental issues related to the notion of multiple levels of granularity. For describing and understanding a problem, we need to explore multiple representations in terms of multiple views and multiple levels of abstraction; for finding the most suitable solutions to problem, we need to examine the space of multiple approximate solutions; in the process of problem solving, we need to employ multiple strategies. In other words, a key to granular computing for machines is to represent and work with different levels of granularity in every stages of problem solving.

One step in machine problem solving is to choose most suitable and accurate representations of the problem. Furthermore, machines must be able to understand and operate on such representations. We consider two levels of representations in terms of multiview and multilevel, as shown in Figure 1. For a problem, we may view it from many different angles, and associate a representation with a particular view. A representation normally makes certain features explicit at the expense of hiding others (Marr, 1982). With each view capturing particular aspects of the problem, the consideration of multiple views may, to some extent, avoid limitations of a single view-level representation (Bateson, 1978; Chen and Yao, 2008). For each view, we may consider multiple levels of abstractions, which each representing the problem at a particular level of details. The multiple levels of abstraction require us to further divide a view-level representation into multiple representations.

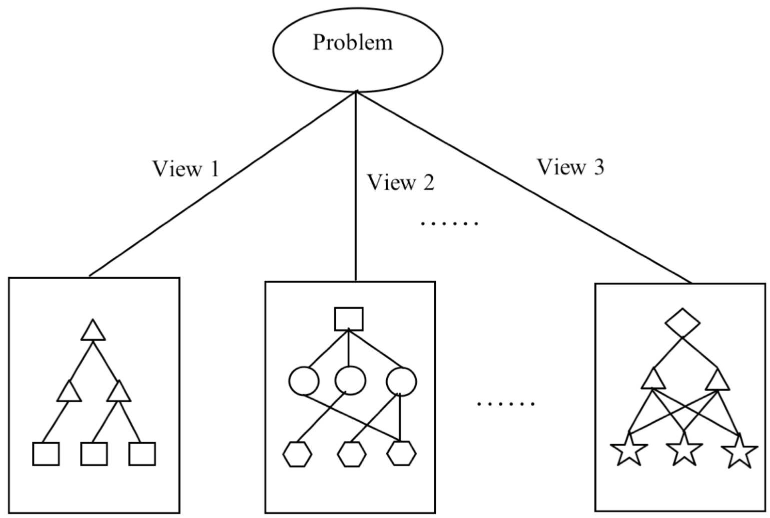

Figure 1. Multiview and multilevel granular structures

In Figure 1, we consider a framework of representations with two levels of granularity: at the view-level, we have multiple representations for different views; within each view, we also have multiple representations for different level of abstraction. In general, one may consider many-level granularity for representation. As another note on representation, one may use different representation languages and schemes in different views and at different levels in each view. Representation schemes and approaches used by humans may provide hints to obtaining good machine representations.

Another crucial task in machine problem solving is to design criteria for evaluating a solution. Due to resource constraints, such as space and time, we may only be able to, or need to, obtain approximate and sub-optimal solutions instead of the optimal solution. For example, in some cases we may only need a qualitative characterization of solutions. This requires a multiple level organization of the space of approximate solutions so that a machine can stop at the appropriate level. The space of approximate solutions reflects the granularity of solutions. When more resources are available, or when new requirements are given, it is possible to search solutions at further levels of accuracy. Finally, the solution space may be related to the problem of representations, so that a particular level of approximate solutions is obtained at the most suitable levels of abstraction and within most suitable views.

With multiple representations of a problem and a multilevel organization of approximate solutions, it comes naturally in the problem solving process to use multiple strategies. In general, problem representation, criteria on solutions, and problem solving strategies work together. It is necessary to choose the most appropriate strategies for obtaining required solutions under particular representation. Furthermore, when one combination fails, it is necessary to search for others; such a switch should also be relatively simple and easy.

To a large extent, the above discussions are based on the Minsky's study on human minds. According to Minsky (2007), human minds are versatile, and some of their features are summarized as follows:

- We can see things from many different points of view; we can rapidly switch among views.
- We have multiple descriptions of things; we develop good ways to organize these representations; we can quickly switch among them.
- We have many ways to ways to think; when one of the ways fails, we can easily switch to another.
- We can learn and create new ways to think.

The requirements of multiple representations, multiple criteria on solutions, and multiple strategies are inspired by humans. Granular computing for machine needs to implement these human-inspired ideas and notions in machines.

6. 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. The triarachic theory can be described by the granular computing triangle as shown in Figure 2. By focusing on multiple level hierarchical structures, the 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 other papers (Yao, 2005, 2006, 2007a, 2008a).

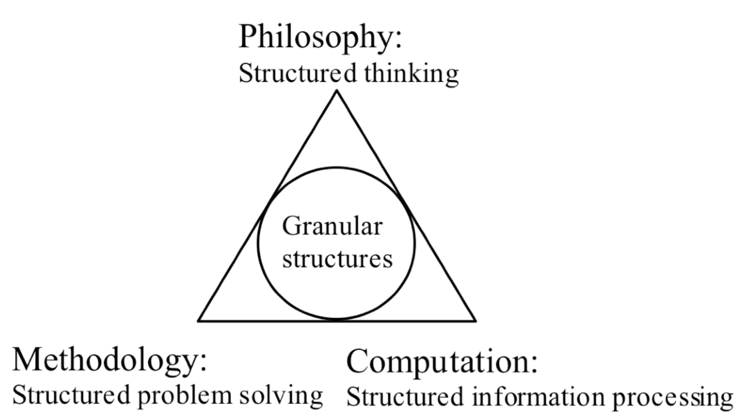

Figure 2. The granular computing triangle

6.1. Granular structures as multiple hierarchies

Granular computing emphasizes on structures. 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. 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 (Simon, 1963). 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. As illustrated by Figure 1, 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.

6.2. The granular computing triangle

The core of the triarchic theory can be simply described by the granular computing triangle of Figure 2. 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 notations. 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.

7. Concluding Remarks

In the chapter, I examine a view of granular computing as a human-inspired paradigm of problem solving and information processing. It covers two types of studies, namely, human-oriented studies and machine-oriented studies, and two goals, namely, granular computing for humans and granular computing for machines. The main stream of research focuses on machine-oriented studies with the goal of granular computing for machines. Human-oriented studies are a prerequisite of machine oriented-studies. As human-inspired structured approaches, granular computing is both for humans and for machines.

I outline a triarachic theory of granular computing based on results from related fields and most recent development of granular computing. The theory is based on granular structures and three perspectives of granular computing. Granular computing emphasizes the use of good structures representing multiview and multilevel. On the one hand, as a philosophy and general methodology, granular computing empowers everyone in problem solving; as a paradigm of structured information processing, granular computing supports human-inspired machines and systems. The triarchic theory enables us to develop granular computing as a field of study, rather than another theory or methodology.

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