Interactive Granular Computing Model for Intelligent Systems

Soma Dutta, Andrzej Skowron

Interactive Granular Computing Model for Intelligent Systems

Soma Dutta[1[0000−0002−7670−3154]] and Andrzej Skowron[2[0000−0002−5271−6559]]

[1] University of Warmia and Mazury in Olsztyn, Poland
soma.dutta@matman.uwm.edu.pl
[2] Systems Research Institute, Polish Academy of Sciences
and
Digital Science and Technology Centre, UKSW, Warsaw
skowron@mimuw.edu.pl

Abstract. The problem of understanding intelligence is treated, by some prominent researchers, as the greatest problem of this century. In this article we justify that a decision support systems to be intelligent there is a need for developing new reasoning tools which can take into account the significance of the processes of sensory measurement, experience and perception about the concerned situations; i.e., understanding the process of perceiving a situation is also required for making relevant decisions. We discuss how such reasoning, called adaptive judgment, can be performed over objects interacting in the physical world using Interactive Granular Computing Model (IGrC). The basic objects in IGrC are called the complex granules (c-granules, for short). A c-granule is designed to link the abstract and physical worlds and to realize the paths of judgments starting from sensory measurement, experience to perception. Some c-granules are extended by information layers, called informational c-granules (ic-granules, for short); they can create the basis for modeling a notion of *control* conducting the whole process of computation over the c-granules.

Keywords: complex granule (c-granule), informational c-granule (ic-granule), control of c-granule, perception of situation, interactive granular computing (IGrC)

1 Introduction

In contrast to the world of pure mathematics, isolated from the real physical world, the present needs of Intelligent Systems (IS) are not met by using only static knowledge; it demands the ability of dynamically learning new information and updating reasoning strategies based on interactions with the dynamical real physical environment. IS often deal with complex phenomena of the physical world. The simplified models, designed for these complex phenomena, are obtained by ignoring the complexities and thus properties derived from such models often do not match with the data gathered by IS in interaction with the environment. This happens as the essence of ignored complexities lacks [1]. This is one of the reasons for developing new computing model for IS. Other reasons follow from the emerging new application areas of IS related to, *e.g.*, Society 5.0 [17] or Wisdom Web of Things (W2T) [21]. It is assumed that in Society 5.0 various social challenges can be resolved by incorporating innovations of the fourth industrial revolution (*e.g.*, Internet of Things (IoT), big data, artificial intelligence (AI), robot and the sharing economy). Similar thought is reflected in [21], where authors described the need for a new area of research, called Wisdom Web of Things (W2T), emphasizing a practical way to realize the harmonious symbiosis of humans, computers, and things in the emerging hyper world, that uses data to connect humans, computers, and things.

So, the object of study no more remains a pure theoretical construct; rather it is a complex system, as stated in [5], connecting abstract information with physical objects: *Complex system: the elements are difficult to separate. This difficulty arises from the interactions between elements. Without interactions, elements can be separated. But when interactions are relevant, elements co-determine their future states. Thus, the future state of an element cannot be determined in isolation, as it co-depends on the states of other elements, precisely of those interacting with it.*

Thus, to understand and reason with complex system or phenomenon we need a new computing model. A model which can (i) continuously monitor (through interactions) some basic properties of the respective real physical configuration associated to the complex system, (ii) learn and predict (more compound or finer) properties/rules for the seen and/or unseen cases based on already stored knowledge, (iii) control the interaction process, as a part of a physical procedure, to reach a desired goal, and (iv) update new information in the knowledge base. The additional concern is that we can only partially perceive these elements and their dynamics; as a result we have only partial description of the states representing these elements and the transition relation representing their dynamics. So, for a new model of computation the main challenges are as follows.

In usual context, for a given family of sets $\{X_i\}_{i\in I}$ by a transition relation we mean a relation $tr_i \subseteq X_i \times X_i$. In the present context, we need to incorporate the components which can specify (i) how elements of X_i are perceived in the real physical environment, and (ii) how the transition relation tr_i is implemented in the real physical world. Existing approaches to soft computing, such as rough sets, fuzzy sets, and other tools used in machine learning lack in considering the above two components. There are two prevalent traditions of mathematical modeling. One is purely mathematical where it is considered that the sets are given. The second is called constructive, where it is assumed that objects are perceived by means of some features or attributes, and only a partial information about these objects in the form of vectors of attribute values is available. Both the tradition of modeling do not take into account how the process of perceiving attribute values is realised, where and how to access the concerned objects in the physical space, and why those attributes are selected. Hence, clearly the perception and action are out of the scope of such practices. However, this is crucial for many tasks dealing with complex phenomena in the real physical world. Thus, *e.g.*, characterization of the state of the complex physical phenomena by a priori given set of attributes becomes irrelevant. From a similar concern, the researchers in [11] proposed to extend Turing test by embedding into it the challenges related to action and perception.

So, how a function representing a particular vague concept is learned from the uses of the community, as well as which parameters to be considered crucial in defining a vague concept and how the values for these parameters are observed or measured, incorporating such information in the model is important for an intelligent agent; otherwise a non-human system cannot derive information about unseen cases. So, we need an extension of the existing approaches where apart from the information about a physical object, a specification of how the information label of a physical object is physically linked to the actual object also can be incorporated.

Keeping in mind the above needs we endorse an approach, called *Interactive Granular Computing* (IGrC). *Interactive* symbolizes *interaction between the abstract world and the real physical world*, and *Granular Computing* symbolizes *computation over imperfect, partial, granulated information abstracted about the real physical world*. In IGrC [7,18,6,3,2] computations are performed on complex granules (c-granules, for short) which are networks of more basic structures including c-granules with additional information layer (called ic-granules, for short), grounded in the physical reality. A brief description of *c*-granules is presented later.

This paper aims to present basic intuitions behind the new computing model; the target is rather to present the idea, without technicalities, through examples explaining different crucial components of the model. Section 2 presents some basic preliminaries about c-granules and ic-granules. The control of a c-granule is explained in Section 3. In the same section we illustrate how with the help of the control of a c-granule a computation process runs and reaches the goal. The paper ends with conclusions and possible further research directions.

2 Basis of Interactive Granular Computing

The rough sets, introduced by Zdzisław Pawlak [12], play a crucial role in the development of Granular Computing (GrC) [19,14,15]. The extension of GrC to IGrC (initiated by Skowron and co-workers [18,6]; see also publications about IGrC listed at `https://dblp.uni-trier.de/pers/hd/s/Skowron:Andrzej`), requires more generalization of the basic concepts of rough sets and GrC. For instance, it is needed to shift from *granules* to *complex granules* (including both physical and abstract parts), information (decision) systems to interactive information (decision) systems as well as methods of inducing hierarchical structures of information (decision) systems to methods of inducing hierarchical structures of interactive information (decision) systems. IGrC takes into account the granularity of information as used by humans in problem solving, as well as interactions with (and within) the real physical world. The computations are realized on the interactive complex granules and that evolve based on the consequences of the interactions occurring in the physical world. Hence, the computational models in IGrC cannot be constructed solely in an abstract mathematical space. In this context, the following quote of Immanuel Kant ([16], p. 4) is relevant to ponder over: [...] *cognition is the result of the interaction of two independent agents, the mind and the real object.*

The proposed model of computation based on complex granules seems to be of fundamental importance for developing intelligent systems dealing with complex phenomena, in particular in such areas as Data Science, Internet of Things, Wisdom Web of Things, Cyber Physical Systems, Complex Adaptive Systems, Natural Computing, Software Engineering, applications based on Blockchain Technology, etc [6,2]. Our proposal is consistent with the thought envisaged in [9]: [...] *cognition is possible only when computation is realized physically, and the physical realization is not the same thing as its description. This is because we also need to account for how the computation is physically implemented*.

We assume that physical objects exist in the physical space as parts of it, and they are interacting with each other. Thus, some collections of physical objects create dynamical systems in the physical space. Properties of these objects and interactions among them can be perceived by so called complex granules (c-granules). To design the c-granules with the ability of perceiving physical objects and their interactions, which is required to achieve the goal of the computation, we use a notion control of a c-granule based on informational complex granules (ic-granules) and a special kind of reasoning, called judgment. Informational complex granules (ic-granules) are constructed over two basic sets of entities: abstract and physical; we may count these two sets of entities respectively as informational (I) and physical (P) objects.

Abstract entities of the ic-granules are families of formal specifications of spatio-temporal windows labelled by information in a formal/natural language specific for a given c-granule or a family of c-granules. The information may be of different kinds and may have different forms. One of the ic-granules also encodes in its information layer the local (discrete) time clock and enables the model to perceive features of physical objects at different moments of time and to reason about their changes. The information layer may contain formulas and their degrees of satisfiability at a given moment of time on some physical objects, as well as the formal specifications of the spatio-temporal windows indicating the location and time of those physical objects.

The physical layer of any ic-granule is called the c-granule and is divided into three parts: soft_suit, link_suit and hard_suit. Each of these parts is a collection of physical objects. The hard_suit consist of the physical objects that are to be perceived The soft_suit is considered to have those objects which are directly accessible at a particular point of time. The objects in the link_suit create, in a sense, a physical pointer that links objects from the soft_suit to the hard_suit; this in turn helps to propagate interactions among physical objects of hard_suit and soft_suit. Directly accessible objects are those for which some features or their values can be directly measurable, or their changes in successive moments of local time of the c-granule can be directly measurable, or some features can be directly changed by the control, discussed in the next section.

Intuitively during the process of computation the behavior of an ic-granule g is modeled cyclically by the control (localised in the ic-granule controlling g). Each cycle starts from a current family, called configuration, of ic-granules containing a distinguished ic-granule with information representing the perception of the current situation. Each cycle consists of several steps such as modification, deletion, suspension of ic-granules or generation of some new ic-granules from the current configuration. In this process a special role is played by the so called implementational ic-granules. Once a new configuration of ic-granules is created the control measures features of some new physical objects in the scope of the newly developed ic-granules and/or matches or aggregates information with that of the previous ic-granules. After gathering perception about the current situation it takes relevant action based on the goal of the computation process. [3]

An ic-granule, in its information layer, contains a formal specification of its scope, i.e., specification of the spatio-temporal window referring to the physical space where the perception process of the ic-granule is localized. Information perceived by the ic-granule can be either by (i) measuring features of the directly accessible objects of the ic-granule, or by (ii) applying reasoning on the already perceived information about the physical objects and their interactions in the scope of the ic-granule and the domain knowledge. The reasoning has to be robust with respect to the interactions from outside of the given scope. The robustness can be up to a degree depending on the formal specification of the scope and is specified in the information layer of the ic-granule.

The task of the above discussed ic-granule is to perceive properties of some part of the physical space lying in its scope. Such ic-granules, denoted as g_s, are perception oriented ic-granules. An ic-granule also can come into play in order to generate/modify new ic-granules. In such case the information layer of the concerned ic-granule contains the information related to the formal specification of the ic-granules to be generated/modified; such an ic-granule is called a planner ic-granule. The formal specifications of such a planner ic-granule can be (i) constraints on specifications of required spatio-temporal windows, satisfiability of which is necessary for activation of the granule to be generated/modified, (ii) specification of procedure for activating new granule, (iii) conditions concerning the expected behaviour of the granule to be generated expressed, (iv) acceptable variations of the expected properties of the ic-granule to be generated, etc.

Another special kind of ic-granule is responsible for storing relevant knowledge required for a process of computation. The relevant information about some contextual part of the computation can be encoded in an object in the soft_suit of this ic-granule; the soft_suit here can be considered as buffer or an internal memory. The link_suit is constructed out of the physical objects creating transmission channel to the hard_suit, which contains the hard disk where the information may have been be stored.

The ic-granules pertaining to perception, plan and knowledge still relate to the abstract part of an computation. However, in contrast to other approaches the ic-granules are themselves made of both abstract and physical entities. Now the above mentioned implementational ic-granules (g_i) come to play for implementation part of a computation process. Based on the perception of the environment available from g_s, general laws available from g_{kb}, a general plan is specified at the information layer of the planner ic-granule at some time point say t_0. Let us call this planner ic-granule evolved at t_0 as g_0. The abstract plan available at g_0 now gets translated by a relevant implementational ic-granule to a low level or implementation level language.[4] This low level language can be different based on context. For example, in a computer-run method the translation to a low level language can be translation of a program code, written in a language, to

[3] The case when some ic-granules from configuration have their own control will be considered elsewhere.

[4] This decomposition process is related to information granulation and the Computing with Words paradigm introduced by Lotfi Zadeh [20] as well as to the challenge discussed by Judea Pearl in [13].

binary code. Thus, the implementational ic-granule carries the abstract description of a computation to a real physical realization.

Let us consider an example of an ic-granule g_s whose scope corresponds to a configuration of objects containing a blind person [10] or a robot with a stick and the objects lying in the surrounding environment. The person/robot and the top part of the stick are directly accessible and belong to the soft_suit. The part of the stick, which is distant from the direct touch of the person/robot, belongs to the link_suit; it links the objects beyond direct accessibility, such as holes, stones lying in the surrounding environment; i.e., in the hard_suit of g_s. The already perceived information about the objects in g_s is stored in an information layer attached to the soft_suit of g_s [5].

3 Control and computation over ic-granules

The control of a c-granule (or control of a computation process) aims to satisfy the current needs of the c-granule. For a given moment of time of the c-granule, the control has access to a family of ic-granules of the c-granule; thus, it has access to the information layers of those ic-granules, using which it directs a kind of complex game among these ic-granules as well as the environment to generate a new configuration of ic-granules from the existing one.

Formal specification of many complex tasks may be thought of as a complex game [18,6] consisting of a family of complex vague concepts, labeled by actions or plans that to be performed when the concepts are satisfied to a satisfactory degree. These complex vague concepts can be invariants that should be preserved to a satisfactory degree, conditions representing risk perceived in the environment, safety properties of the computation, quality of the current path toward achieving the goals, or risk indicating current needs are no longer achievable. These complex vague concepts (usually described in a fragment of a natural language) should be learned from data and domain knowledge with the use of physical laws. Moreover, the concepts as well as the labels in a complex game can evolve in time. Hence, control should have some adaptive strategies allowing relevant modification of the complex game.

3.1 Two kinds of transition properties of ic-granules realised by control

Properties of physical objects in the scope of a c-granule and their interactions are perceived by the control of the c-granule. At a given moment of local time t, the behaviour of the control depends on the existing ic-granules belonging to its scope, often called the configuration of ic-granules at t.

The control of a c-granule at time point t performs a reasoning using the current configuration of ic-granules which includes a distinguished ic-granule g_s incorporating information of the perceived situation. In the information layers of these ic-granules there are formal specifications of the precondition α that to be satisfied during the generation/modification of a new ic-granule and a postcondition β describing expected properties to be satisfied after generation/modification of the new ic-granule. The pairs of

[5] In [6] this example is elaborated using c-granules without informational layers where encoding information from soft_suit is made by an external observer.

the form (α,β) create the family of expected transition properties, denoted as $\mathcal{R}_I$. After initiation of the ic-granule generation/modification process through some implementation ic-granule and embedding the implementation process through the real physical objects, a property of the new configuration, say γ is derived from data gathered about the behaviour of new configuration. Then control performs reasoning (using β,γ and domain knowledge) to estimate the degree of matching of the expected condition β with the observed property γ. The pairs of the form (α,γ) create the family of real (physical) transition properties, denoted as $\mathcal{R}_P$. The pair $\mathcal{R} = (\mathcal{R}_I, \mathcal{R}_P)$ describes the expected and actual transition properties among the ic-granules. The information associated to different ic-granules included in the control determines the dynamics of the transition among the ic-granules of a particular c-granule. Hence, $\mathcal{R}_I$ specifies a piece (or a set of pieces) of information that is expected to describe the next state of the computation.

Let us consider that at some time t the computation is taking place at the ic-granule g_{sub}. The information label of g_{sub}, say $inf_{g_{sub}}$, specifies the perceptual properties of the state of the environment. The information $inf_{g_{sub}}$ along with the relevant knowledge $inf_{g_{kb}}$ from g_{kb} points to the information $inf_{g'_{sub}}$, describing the next possible state. So, $(\{inf_{g_{sub}}, inf_{g_{kb}}\}, inf_{g'_{sub}})$ is an outcome of $\mathcal{R}_I$ indicating g'_{sub} is the next expected configuration of the ongoing computation. Contrary to $\mathcal{R}_I$, $\mathcal{R}_P$ specifies a relation among the actual objects lying in the scope of the current ic-granule g_{sub}. Let this actual real physical interrelation among the objects of g_{sub} at time t be encoded by $inf_{g_{sub}^{S-L-H}}$; this refers to the information concerning objects in the three suits of g_{sub} which becomes available after initiation of some interactions. Let after initiation of interactions the obtained configuration at time point t_n be described by the information $inf_{g_{sub}}^{t_n}$. The properties of obtained ic-granule $g_{sub}^{t_n}$ can be different from the expected ic-granule g'_{sub}. Thus, unlike the transition relation in an automata the transition from one ic-granule to another is not completely defined a priori, and depends on both $\mathcal{R}_I$ (specification of the expected transition properties) and $\mathcal{R}_P$ (specification of the real transition properties).

We know that control of a c-granule is responsible for generating new configuration of ic-granules from the current ones. This dynamic process of changing from one configuration to other is carried out by the control in a cyclic order by using the relevant information localized in the currently existing ic-granules in the control and based on the aggregation of $\mathcal{R}_I$ and $\mathcal{R}_P$. But to create a new configuration of ic-granules it is needed to embed the above relevant information, gathered from the ic-granules at time t, to an implementational ic-granule g_i. Thus, from the formal specifications of ic-granules the physical realizations process is initiated by some implementational ic-granules. This process may involve updating, canceling or suspending some of the existing ic-granules from time t. Once a new configuration of ic-granules is created the process of perceiving the properties of the new state of the environment, verifying the degree of matching of the generated configuration with the expected one, and coupling them with relevant domain knowledge, starts. This marks the starting of a new cycle of the control at the next time point. The configurations of ic-granules at each cycle are represented by different layers of the process of computation. Through these layers the decomposition of formal specification is realised in a step-by-step manner to make it closer to the real physical environment of the computation.

3.2 Computation over the ic-granules directed by control

This section presents how during a computation process different parts of different ic-granules participate and how based on both $R_{\mathcal{I}}$ and $R_{\mathcal{P}}$ the computation moves from one layer to another layer. We assume that at time t_0 some properties of a part $S \subseteq \mathcal{P}$ are available in $\mathcal{I}$. The information related to the perceived properties of objects corresponding to the window specifications describing the space-time hunks of S form the informational layer of an ic-granule, denoted as g_s; the physical objects surrounding S form the soft_suit, link_suit and the hard_suit of g_s. The objects which are directly accessible, or about which already some information is perceived, belong to the soft_suit of g_s. The objects in S, about which some information can be gathered only after performing some physical interactions with them, belong to the link_suit and hard_suit of g_s. Thus, objects between soft_suit and hard_suit are connected by a collection of objects forming a link from directly accessible to not directly accessible objects. The information part is attached to the soft_suit of g_s, and works as a label of g_s. Further steps of the computation are as follows.

Layer-0

(i) At t_0, the beginning of the control's cycle, g_s is labelled with the perceived information of the directly accessible objects of S. The target is to create a communication channel through the directly accessible objects so that objects lying in the hard_suit of g_s can be accessed to move forward the purpose of the computation. An example of g_s can be regarded as the ic-granule having in its scope a blind person or robot with a stick and the objects lying in the surrounding.

(ii) The description of the goal is attached as the information layer of g_0, a planner ic-granule at time t_0. In the context of our example, the goal can be moving forward avoiding the obstructions such as holes/stones in the hard_suit of g_s. So, g_0 consists of those particular cells of a human brain that have analytical functionalities. In case of a robot, g_0 is the part where the goal description of the robot is set.

(iii) To have perception about objects from the link_suit and hard_suit of g_s relevant knowledge about the environment from g_{kb} is sought for. The information layer of g_{kb} is labelled with the address to those relevant properties of the fragment of S. The soft_suit of g_{kb} has those objects which are like outer box of the memory location whose address is attached to the information layer; in order to access the detailed information about S some more inner boxes are to be opened. Keeping analogy to a computer memory, we can think of an outer folder containing some inner folders directing to the main folder. The name of the outer folder along with its path address is attached as the label of g_{kb}. In regard to the above example, g_{kb} can be considered as the part of the brain related to memory locations consisting of previous experiences of such environment.

(iv) Aggregating the perceptual information labelled at g_s, goal labelled at g_0, and information pertaining to experiences labelled at g_{kb}, the plan available at g_0 is decomposed in detail. This detailed plan is labelled at the ic-granule g_1 at the next time point t_1. For a visual representation the readers are referred to Figure 1.

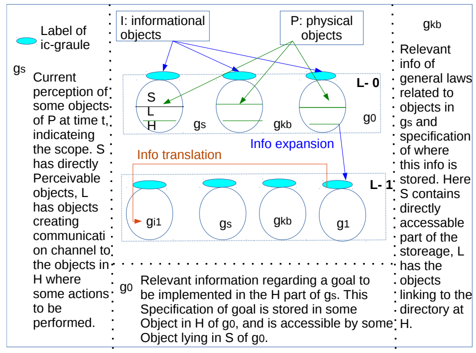

Fig. 1. Computation over ic-granules passing from layer-0 to layer-1

Layer-1

(i) The new plan attached to g_1 is a result of the informational relation $\mathcal{R}_I$ applied on the information associated to g_s, g_{kb} and g_0; that is plan in g_1 specifies the next state description of the plan. In the case of the example, at t_0 the information label of g_0 encodes the goal of the person that primarily registered in the brain, the soft_suit of g_0; the hard_suit of g_0, such as more deep analytical brain cells, remains still unaccessed. Combining information of g_s and g_{kb} at time t_1 the person digs into those analytical cells; thus interaction with the previously unaccessed part of g_0 happens. Gradually hard_suit of g_0 becomes accessible, and the hard_suit of g_0 becomes the soft_suit of g_1, labelled with further detailed plan.

(ii) Now in order to implement the abstract description of the plan available at g_1 through a real physical action, the plan needs to be transformed from the abstract level to an implementational level language. From the perspective of our example, this can be translation of the plan from the person's analytical brain cells to a language of actuators, like hands, legs, and the stick of the person. So, a new ic-granule is manifested at this layer. We call it as g_{i_1}, an implementational ic-granule. To be noted that g_{i_1} does not concern about the actual actuators; rather it is like another hard-drive in the brain of the person where the action plan can be stored in the language of actuators. The information layer of g_{i_1} also contains the specification of conditions for initiating the implementation plan through a real actuator.

Layer-2

(i) The specification of implementation plan of g_{i_1} is now realized through a physical object at time t_2. Let this object belong to the scope of the ic-granule g_2. In case of the example, it can be the stick of the blind person on which the abstract implementation plan is embedded, and g_2 represents the ic-granule containing the stick in its scope. Once the $inf_{g_{i_1}}$, the specification stored in g_{i_1}, is embedded on a real physical object, namely the stick, the role of $\mathcal{R}_P$ comes into play. The physical interaction of the stick with other objects in g_2 is encoded in the relational language of $\mathcal{R}_P$ in the information layer of g_2. If inf_{g_2} matches to a significant level to the condition for initiating implementation plan stored at $inf_{g_{i_1}}$ then an action compilation signal is passed to the next implementation granule g_{i_2}.

(ii) With the action compilation specification of g_{i_2} the objects lying in its link_suit and hard_suit propagates actions to realize a desired configuration in the hard suit of g_s. In the context of our example, g_{i_2} represents the ic-granule which specifies how to move the stick forward until it touches a stone on its way. This chain of objects between the stick and a stone creates a communication channel.

(iii) Through this communication channel the computation process enters into the hard_suit of g_s, which was unaccessible at time t_0. The initiation of the action compilation via g_{i_2} creates a link to the hard_suit of g_s. This new interaction gives access to the hard_suit of g_s which was previously unaccessible.

(iv) A new cycle starts by perceiving properties of the newly accessible part of g_s.

4 Reasoning in the context of complex granules: future directions

In order to realize the above model, different kinds of reasoning strategies need to be incorporated. As the model couples the abstract information with its real physical semantics, the reasoning methods cannot only focus on deriving information from information; it needs to perform reasoning based on sensory measurements and perception too. Moreover, as ic-granules contain different heterogeneous forms of information, we need different forms of reasoning apart from abduction, deduction, induction.

For example, in the process of connecting a specified spatio-temporal window with its real physical semantics and transiting from one configuration of ic-granules to another the control needs to decide (i) which windows from the current configuration should remain active and which is to be suspended, (ii) when and how a new window need to be opened and implemented in the real physical space, (iii) how much variation between the real and expected information can be allowed, (iv) how to generate a window specification from measured values of attributes, (v) how to induce a relevant set of attributes classifying a window, etc. There can be many other aspects of reasoning related to hierarchically learning and improving each step of the computation process evolving from one layer of ic-granules to other. All these directions need a further exploration and expansion in order to develop an intelligent agent which is not restricted to behave just based on what it is taught once; rather can learn to adopt new strategies based on continuous interaction with the real physical environment.

Acknowledgement. Andrzej Skowron was partially supported by the ProME (Prognostic Modeling of the COVID-19 Epidemic) grant.

References

1. Brooks, F.P.: The Mythical Man-Month: Essays on Software Engineering. Addison-Wesley, Boston (1975) (extended Anniversary Edition in 1995)

2. Dutta, S., Jankowski, A., Rozenberg, G., Skowron, A.: Linking reaction systems with rough sets. Fundamenta Informaticae **165** (2019) 283–302 (https://doi.org/10.3233/FI-2019-1786)
3. Dutta, S., Skowron, A., Chakraborty, M.K.: Information flow in logic for distributed systems: Extending graded consequence. Information Sciences **491** (2019) 232-250 (https://doi.org/10.1016/j.ins.2019.03.057)
4. Gerrish, S.: How Smart Machines Think. MIT Press, Cambridge, MA (2018)
5. Gershenson, C. and Heylighen, F.: How can we think the complex? In: K. Richardson, (Ed.): Managing Organizational Complexity: Philosophy, Theory and Application. Information Age Publishing, pp. 47-61 (2005)
6. Jankowski, A.: Interactive Granular Computations in Networks and Systems Engineering: A Practical Perspective. Lecture Notes in Networks and Systems. Springer, Heidelberg (2017) (https://doi.org/10.1007/978-3-319-57627-5)
7. Jankowski, A., Skowron, A.: A Wistech paradigm for intelligent systems. Transactions on Rough Sets: Journal Subline **6** (2007) 94–132 (LNCS 4374; Springer, Heidelberg) (https://doi.org/10.1007/978-3-540-71200-8_7)
8. Martin, W.M., ed.: Theories of Judgment. Psychology, Logic, Phenomenology. Cambridge University Press, Cambridge, UK (2006)
9. Miłkowski, M.: Explaining the Computational Mind. The MIT Press, Cambridge MA (2013)
10. Nöe, A.: Action in perception. MIT Press, Cambridge, MA (2004)
11. Ortiz Jr., C.L.: Why we need a physically embodied Turing test and what it might look like. AI Magazine **37** (2016) 55–62 (https://doi.org/10.1609/aimag.v37i1.2645)
12. Pawlak, Z.: Rough sets. International Journal of Computer and Information Sciences **11** (1982) 341–356
13. Pearl, J.: Causal inference in statistics: An overview. Statistics Surveys textbf3 (2009) 96–146 (https://doi.org/10.1214/09-SS057
14. Pedrycz, W., Skowron, S., Kreinovich, V., eds.: Handbook of Granular Computing. John Wiley & Sons, Hoboken, NJ (2008)
15. Pedrycz, W.: Granular computing for data analytics: A manifesto of human - centric computing. IEEE/CAA Journal of Automatica Sinica **5** (2018) 1025–1034 (https://doi.org/10.1109/JAS.2018.7511213)
16. Pietarinen, A.V.: Signs of Logic Peircean Themes on The Philosophy of Language, Games, and Communication. Springer, Heidelberg (2006)
17. Salgues, B.: Society 5.0. Industry of the Future, Technologies, Methods and Tools. ISTE, London and Wiley, Hoboken, NJ (2018)
18. Skowron, A., Jankowski, A., Dutta, S.: Interactive granular computing. Granular Computing **1**(2) (2016) 95–113 (https://doi.org/10.1007/s41066-015-0002-1)
19. Zadeh, L.: Toward a theory of fuzzy information granulation and its centrality in human reasoning and fuzzy logic. Fuzzy Sets and Systems **90** (1997) 111–127 (https://doi.org/10.1016/S0165-0114(97)00077-8)
20. Zadeh, L.: Computing with Words: Principal Concepts and Ideas. Studies in Fuzziness and Soft Computing **277**, Springer, Heidelberg (2012) (https://doi.org/10.1007/978-3-642-27473-2)
21. Zhong, N., Ma, J.H., Huang, R.H., Liu, J.M., Yao, Y.Y., Zhang, Y.X., Chen, J.H.: Research Challenges and Perspectives on Wisdom Web of Things (W2T). Journal of Supercomputing **64**(3) (2013) 862–882 (https://doi.org/10.1007/s11227-010-0518-8)