



Granular Computing and Three-way Decisions for Cognitive Analytics

JingTao Yao¹ · Yiyu Yao¹ · Davide Ciucci² · Kaizhu Huang³

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Inspired by the human cognitive processes and human intelligence, cognitive analytics concerns the philosophy, theory, and application of cognitive computing in various fields. Cognitive data analytics, in particular, consider the structures and semantics of data for better description, prediction, and decision-making. Granular computing and three-way decisions are two fields of research on human-inspired computation. Granular computing takes advantage of data abstraction and reasoning at multiple levels of granularity. Three-way decision and three-way computing explore thinking, problem solving, and information processing in threes, namely triads of three things. These three paradigms of computing have been investigated in business, management, medical sciences, natural sciences, and engineering. They have been applied in data mining, data analytics, machine learning, artificial intelligence, and many other areas.

Cognitive computing, granular computing, and three-way computing share a large overlapping research agendas. Granular computing and three-way decisions offer new theories, models, and tools for cognitive analytics. This special issue represents the state of the arts of granular computing and three-way decisions for cognitive analytics. The collection of twenty-four papers addresses theoretical and applicational aspects of cognitive analytics, granular computing, and three-way decisions. By encouraging the communication, interaction, and integration of the three fields, this special

issue is, in fact, a showcase and an illustration of the three-way decision as thinking in threes.

Theory and Applications of Granular Computing

The paper authored by He, Yu, Gu, and Zhang, *A Multi-Granularity Information Based Method for Learning High Dimensional Bayesian Network Structures*, proposes a method to solve the problem of learning the structure of high-dimensional Bayesian networks. To optimize the structure search space and reduce the complexity of structure learning, a multi-granularity information-based learning model is proposed. The model can effectively learn Bayesian network structures from high-dimensional data. It can also improve the efficiency and accuracy of score-based methods by embedding them into the model.

The paper authored by Liu, *Attribute Reduction Algorithms Determined by Invariants for Decision Tables*, discusses the mathematical structures of attribute reduction with respect to invariants and provides different algorithms to solve the reduction problem. This notion of reduction invariants provides a new perspective on attribute reduction.

The paper authored by Zhang, Fan, Chen, Tang, and Lv, *Classification-level and Class-level Complement Information Measures based on Neighborhood Decision Systems*, proposes three-way complement information measures at the classification level and class level of extended neighborhood decision systems, as well as degenerated equivalence decision systems. The four criss-cross modes of three-way measures exhibit horizontally extended and degenerated isomorphisms and hierarchically decomposed and integrated isomorphisms or combined isomorphisms. The metric granulation nonmonotonicity and monotonicity are acquired, respectively, in neighborhood and equivalence decision systems.

The paper authored by Xin, Song, Xue, Sun, and Peng, *Multi-granular Intuitionistic Fuzzy Three-Way Decision Model based on the Risk Preference Outranking Relation*,

✉ JingTao Yao
jingtiao.yao@uregina.ca

Yiyu Yao
yiyu.yao@uregina.ca

Davide Ciucci
davide.ciucci@unimib.it

Kaizhu Huang
kaizhu.huang@dukekunshan.edu.cn

¹ University of Regina, Regina, Canada

² University of Milano-Bicocca, Milan, Italy

³ Duke Kunshan University, Suzhou, China

proposes a multi-granular intuitionistic fuzzy three-way decision model based on the concept of risk preference outranking relation. The model is verified with a case study analysis and comparisons with some existing methods. The results show that the proposed model can quantitatively analyze and calculate the uncertainty of decision-makers' cognitive risk preferences, achieve global control of the decision-making process, and reduce the loss of decision-making costs.

The paper authored by Wan, Li and Wei, *Optimal Granule Combination Selection based on Multi-granularity Triadic Concept Analysis*, discusses granularity of triadic contexts, cross-granularity knowledge discovery, and optimal granule combination selection in multi-granularity triadic contexts. The main contribution is to incorporate the multi-granularity idea into triadic concept analysis and to realize the cross-granularity conceptual analysis of three-dimensional data.

The paper authored by Xue, Sun, Hou, Pang, and Zhang, *Three-Way Decision Models based on Multi-granulation Rough Intuitionistic Hesitant Fuzzy Sets*, proposes four multi-granulation rough intuitionistic hesitant fuzzy set models and their corresponding three-way decisions methods. It extends the theoretical connotation and application scenario of the existing three-way decision method.

The paper authored by Zhang, Min, Chen, Shen, Wen, and Zhou, *Tri-partition State Alphabet-based Sequential Pattern for Multivariate Time Series*, enriches the application of three-way decision theory in the field of sequence pattern discovery. The novel notion of state transition patterns based on two reasonable tri-partition strategies can provide more practical semantics and concise results.

Theory and Applications of Three-way Decisions

The paper authored by Qi, Wei, and Ren, *3-Way Concept Analysis based on 3-Valued Formal Contexts*, proposes the notion of 3-valued formal context and adopts 3-way concept analysis to construct 3-valued concept lattice. The 3-valued concept lattice can represent potentially new types of information and structure of 3-valued formal context and may offer a new model for cognition.

The paper authored by Yang, Miao, and Zhang, *3W-AlignNet: A Feature Alignment Framework for Person Search with Three-way Decision Theory*, proposes a three-way based feature alignment framework or 3W-AlignNet to optimize the re-ID feature localization in existing end-to-end person search models. The framework is implemented by iterative operations. Three-way decision theory is applied to avoid the IoU mismatch problem. Extensive experiments show that the method outperforms all

other state-of-the-art end-to-end methods on two widely used person search datasets, namely CUHK-SYSU and PRW.

The paper authored by Zhao, Ma, Li, and Luo, *A Multi-Criteria Three-way Decision Making Method in a Picture Fuzzy Probabilistic Decision System*, proposes a multi-attribute three-way decision method by combining picture fuzzy sets, picture fuzzy point operators, three-way decision, and multi-criteria decision-making to solve multi-attribute decision-making problems from a new perspective. Through a project investment example, the proposed method is compared with the existing methods, which shows that the proposed method is reasonable and effective.

The paper authored by Liu, Chen, Zhang, and Wang, *A Novel Functional Network based on Three-way Decision for Link Prediction in Signed Social Networks*, presents a novel functional network framework based on three-way decision theory. The framework is not only an explainable framework but also has outstanding performance. The improved functional network may be a good replacement for deep neural networks in some fields.

The paper authored by Yang, Zhang, and Qin, *Constructing Robust Fuzzy Rough Set Models Based on Three-way Decisions*, discusses the construction of robust fuzzy rough set models from a three-way decision perspective. According to the idea of three-way approximations, the fuzzy similarity degree and lower and upper approximations are proposed by introducing a pair of thresholds, respectively. Four fuzzy rough set models are selected from the sixteen constructed fuzzy rough set models to verify the better robustness of the improved model based on three-way approximations over the two-way methods with respect to the original models and two types of data noise.

The paper authored by Zhang, Chen, Wang, and Wang, *Improving Incremental Nonnegative Matrix Factorization Method for Recommendations based on Three-way Decision Making*, constructs a three-way incremental non-negative matrix factorization algorithm by using the idea of three-way decision. The algorithm aims at the problem that the prediction error increases when the incremental non-negative matrix factorization. It is applied to the rating prediction scenario of recommendation system. In the process of recommendation decision, the algorithm can ensure the error does not increase and the prediction effect is better than the existing methods.

The paper authored by Zhao and Miao, *Isomorphic Relationship Between \mathbf{L} -three-way Concept Lattices*, discusses the relationship between \mathbf{L} -two-way concept lattices and between \mathbf{L} -three-way concept lattices. It shows that the eight types of \mathbf{L} -two-way concept lattices constitutes two isomorphic groups, and the four types of \mathbf{L} -object-induced three-way concept lattices, as well as the four types of \mathbf{L} -attribute-induced three-way concept lattices, are isomorphic, respectively.

The paper authored by Jiang, Guo, and Duan, *Measure Effectiveness of Change-based Three-way Decision Using Utility Theory*, presents an approach to analyzing and measuring the effectiveness of three-way decision by using utility theory. Based on the change of an object itself under the action of strategies, two views are used, namely the top-down and the down-top views. The former allows measuring the effectiveness of the trisection and the latter allows obtaining a reasonable trisection.

The paper authored by Hu, *Three-way Bayesian Confirmation in Classifications*, presents a new perspective of classifications that trisects the descriptions of objects into three confirmatory, disconfirmatory, and neutral regions based on Bayesian confirmation theory. The presented model focuses on the impact of descriptions on the classification of objects, which is evaluated by quantitative Bayesian confirmation measures that compare the prior and posterior probabilities.

The paper authored by Lang, *Three-way Conflict Analysis: Alliance, Conflict, and Neutrality Reducts of Three-valued Situation Tables*, discusses issue reduction in three-valued situation tables for three-way conflict analysis. The set of reduced issues consists of the key issues for remaining the alliance relation, neutrality relation, and conflict relation.

The paper authored by Chen, Liu, and Zhang, *Three-way Decision Making based on Data Envelopment Analysis with Interval Data*, presents a novel three-way DEA model by introducing three-way decision to interval DEA model. The paper first constructs a hybrid decision matrix by combining the matrix of inputs and outputs from DEA model and the matrix of loss function from three-way decision. It then proposes a new method to acquire the conditional probability, and develop three strategies to calculate their corresponding decision risks according to the principle of minimum decision risk. Finally, a full ranking for all DMUs under the three strategies, as well as their generated decision rules, are investigated.

The paper authored by Yue, Chen, Yuan, and Lv, *Three-way Image Classification with Evidential Deep Convolutional Neural Network*, proposes a three-way classification method based on evidential deep convolutional neural networks to implement the low-risk uncertain classification for images. The evidence theory is utilized to measure the uncertainty of the predictions of neural networks and to construct the evidential deep convolutional neural network for image classification. The proposed method overcomes the drawback of the traditional three-way classification methods on unstructural image data.

Granular Computing and Three-way Decisions for Cognitive Analytics

The paper authored by Hu, Shao, Liu, and Mi, *Cognitive Computing and Rule Extraction in Generalized One-sided Formal Contexts*, proposes a novel method for quantitative association

rule mining based on a generalized one-sided formal context and solid cognitive foundations. The proposed method extracts rules directly in a multi-valued formal context rather than converting the multi-valued formal context into a binary formal context. The experimental results show that the proposed algorithm reduces both time and space costs compared with the classical quantitative association rule mining algorithm.

The paper authored by Zhi and Li, *Granule Description of Incomplete Data: A Cognitive Viewpoint*, presents a simple method to describe basic granules via stable concepts and evanescent concepts, and to approximate indefinable granules via basic granules under the environment of incomplete data. The results show that the ordinary concept-based granule description is more concise and less complex than the approximate concept-based granule description.

The paper authored by Szczuko, Kurowski, Ody, Czyżewski, Kostek, Graff, and Narkiewicz, *Mining Knowledge of Respiratory Rate Quantification and Abnormal Pattern Prediction*, presents a threefold approach to evaluate breathing patterns automatically. First, it uses group reasoning to investigate how to handle data comprising health indicators and breathing signal characteristics, and what machine learning approach should be employed. Second, it follows Yao's three stages of reasoning: perception, cognition, and action in their approach. Finally, it focuses on tri-way reasoning, applying granular computing and rough sets to knowledge mining. Analyses performed by the rough set-based approach are validated employing k-NN. Overall, the results indicate that the proposed method can support the visual assessment of respiratory patterns by an expert. Also, this study shows that the granularity concept applied to respiratory rate quantification and abnormal pattern prediction may provide novel insights into cardiorespiratory regulation beyond those offered by a simple analysis of respiratory rate, inspiration and expiration times, tidal volume assessment, or their variability.

The paper authored by Jia and Shen, *Multimodal Emotion Distribution Learning*, proposes an emotion distribution learning model by introducing multimodal information. Emotion recognition is extended as a label distribution learning problem, which can obtain the intensities of different emotions for each expression at the finest granularity. The proposed model not only retains the advantage of comprehensive information in multimodal learning but also makes full use of valuable semantic information in emotion distribution.

The paper authored by Zhang, Sun, Mi, and Feng *Three-way Decision Models of Cognitive Computing in Pythagorean Fuzzy Environments*, proposes Pythagorean fuzzy loss functions based on three descriptions, adding a hesitation description to the Pythagorean fuzzy environment. It discusses four strategies for dealing with expected losses on the basis of the novel Pythagorean fuzzy loss functions and three-way decision models. The paper also presents an analysis of different parameters to show the feasibility of the decision-making with the proposed model.

Acknowledgements The Guest Editors hope that the scientific communities of granular computing, three-way decisions, and cognitive computing will benefit from this special issue. The twenty-four papers show the diversity of research in the three research areas and the close interactions of the three areas. They not only contribute to our knowledge base but also provide further evidence in support of the philosophy of three-way decision as thinking in threes. The special issue is a result of hard work of authors, reviewers, and editors. The published papers are selected from over 70 submissions through rigorous reviews and several rounds of revisions. We thank all authors who submitted

their work to this special issue. We thank reviewers for their critical and constructive comments, which have greatly improved the final versions. We thank the Editor-in-Chief of Cognitive Computation, Professor Amir Hussain, for his support and encouragement.

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