様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

# 科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Studies on Belief and Opinion Propagation in Multi-Agent Systems

研究課題名（英文）Studies on Belief and Opinion Propagation in Multi-Agent Systems

研究代表者
Ｎｉｃｏｌａｓ　Ｓｃｈｗｉｎｄ（Schwind, Nicolas）

国立研究開発法人産業技術総合研究所・情報・人間工学領域・研究員

研究者番号：６０６４６３９７

交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：人々は日常的にソーシャルメディア上で自らの意見を共有している．特に，企業ブランドへの否定的な内容は急速に広がり，否定的な認識を生み出す可能性があるため，企業への社会認識や世間の評判を理解し監視する必要がある．「信念リビジョンゲーム」(BRG)フレームワークは，このような状況をモデル化するために2015年に導入された．本研究課題では，BRGフレームワークに一連のフォーマルな概念を導入することでBRGフレームワークの高度化を目的とし，下記の研究を行った．

研究成果の学術的意義や社会的意義
本研究課題は国内外の研究者と共同で進め，人工知能分野の難関国際会議4件（3件はランクA*）と難関国際論文誌1件の発表を行った．

研究成果の概要（英文）：Daily, people share their opinions over social media. In particular, negative content regarding a brand could propagate rapidly and generate negative perceptions. So one needs to understand and monitor the public perception and the social reputation of companies. The "Belief Revision Games" (BRG) framework was introduced in 2015 for modeling such situations. This project aimed to enrich the BRG framework by providing a set of formal concepts to be integrated to it: (1) we explained what kind of revision policies the agents use, assuming that they revise their beliefs in a "rational" way; (2) we explained how an agent can be "manipulated", so as to convince all agents in the network of some "goal information" to be disseminated; (3) we introduced algorithms to simulate opinion propagation in a BRG.

研究分野：Knowledge Representation and Reasoning

キーワード：Belief Change　Belief Revision Game　Brand Crisis Management　Belief Promotion　Public Announcement　Multi-Agent System　Propositional Logic　Network of Agents

## １．研究開始当初の背景

Daily, millions of users share their opinions and disseminate breaking news over social media. In particular, negative content regarding a brand could disseminate rapidly over social media and generate negative perceptions. So one needs to understand and monitor the public perception and the social reputation of companies. In a AAAI'15 paper entitled "Belief Revision Games", we have first introduced a framework (called BRG framework) for modelling a network of communicating agents and their beliefs over time; in this setting, each agent revises her beliefs according to her own current beliefs and the beliefs of her acquaintances. This BRG framework is the cornerstone of many further studies aiming to better understand how opinions propagate in a network of agents. This Kakenhi project aimed to provide a set of formal tools to be integrated to the BRG framework.

## ２．研究の目的

Research studies include some answers to the following important points in BRGs:
a) Rationality issues: what kind of revision policies are the agents expected to use, assuming that they revise their beliefs in a "rational" way?
b) Manipulation issues: when an agent in the network is "bribable" or "controllable", what kind of belief/opinion should one promote into her beliefs so as to convince all agents in the network of some piece of goal belief/opinion?
c) Announcement discovering issues: given that an unknown announcement led a set of agents to revise their beliefs and given the prior beliefs and the revised beliefs of the agents, what can be said about the announcement?
d) Computational issues: how hard is it simulate how opinions propagate in a BRG?

## ３．研究の方法

Research was mainly pursued in collaboration with researchers in Japan and abroad:
- CRIL, Artois University, Lens, France: Prof. Pierre Marquis (head of CRIL), Prof. Sebastien Konieczny, Assoc. Prof. Jean-Marie Lagniez.
- LIP6, CNRS and Sorbonne University, Paris, France: Assoc. Prof. Gauvain Bourgne.
- NII, Tokyo, Japan: Prof. Katsumi Inoue.

The goal was to disseminate research results through publications in top Artificial Intelligence venues. As a result, we have got five publications in international venues, three of which are of rank A*, and one of which is a journal publication.

## ４．研究成果

a) Rationality issues:
i) We focused on agents which are reluctant to change: each agent is ready to accept new information coming from the merging of the beliefs of her acquaintances, provided that it allows her to refine her prior beliefs but does not question them. Thus, the revision policy which is adopted by each such agent consists in expanding her belief base by the resulting merged base if the conjunction is consistent, and to keep it unchanged otherwise. In order to avoid the latter case, we defined a new class of belief change operators called consensus operators, i.e., merging operators such that the merged set of beliefs C that is generated satisfies the consensus rationality postulate: C is consistent with every input piece of belief that is consistent with some integrity constraint. So in a nutshell, this new rationality postulate imposes the merged base to be consistent with the pieces of information provided by each agent involved in the merging process. We studied the interplay of this new postulate with the standard so-called IC postulates for belief merging, and proved an incompatibility result. We exhibited the maximal sets of IC postulates which are consistent with the consensus postulate are exhibited. When satisfying some of the remaining IC postulates, consensus operators were shown to suffer from a weak inferential power. To fill the informational gap, we introduced two families of consensus operators having a better inferential power by setting aside some of these postulates.

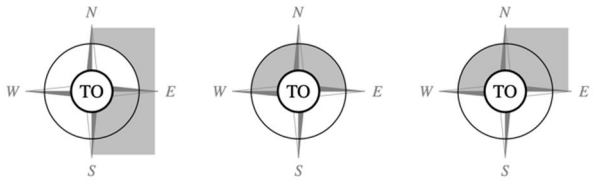
*Related publication:*
*- Nicolas Schwind, Pierre Marquis. "On Consensus in Propositional Merging". The 32nd AAAI*

*Conference on Artificial Intelligence (AAAI'18), pages 1949-1956. New Orleans, LA, USA, February 2018.*

ii) Because existing belief merging operators take advantage of all the models from the input agents' beliefs, including those contradicting the integrity constraint, we argued that this is not suited to every merging scenario, especially when the integrity constraint encodes physical laws. In that case the input beliefs have to be "rationalized" with respect to the integrity constraint during the merging process. We defined several conditions characterizing the operators that are independent to such a rationalization process, and we showed how these conditions interact with the standard IC postulates for belief merging. Especially, we gave an independence-based axiomatic characterization of a distance-based operator.

*Related publication:*
*- Nicolas Schwind, Sebastien Konieczny, Pierre Marquis. "Belief Base Rationalization for Propositional Merging". Journal of Logic and Computation, 28(7):1601-1634. October 2018.*

**b) Manipulation issues**:
This part of research consisted in determining what "promoting" means: indeed, once we have formalized the notion of belief promotion, we can ask ourselves what kind of information one must convey to a bribable agent so as to propagate a goal belief in the network. So intuitively, "promoting" consists in replacing an agent's belief by some information that is "closer" to some goal belief, and we could show that this can be done in a purely qualitative way. Consider the following simple example depicted on the figure. Assume an agent's initial belief is B1: the post office (PO) is located east of the town office (TO), and if it's north-east then PO should be far from TO. Now, the agent hears B2 from someone else: PO is north, close to TO. One can see that the new information B2 contradicts the agent's initial belief B2. To take advantage of both B1 and B2 while maintaining the consistency of the agent's belief, one promotes B2 into B1, which consists in building a belief in-between B1 and B2. The belief B12 is an appropriate candidate for this aim. So in our work, we formalized the notion of promotion in terms of a set of rationality postulates, and provided a representation theorem in terms of minimal change. We also showed that this class of operators is a very general one, since it captures as particular cases belief revision, commutative revision, and (essentially) belief contraction.



(a) $B_1$ (b) $B_2$ (c) $B_{12}$

*Related publication:*
*- Nicolas Schwind, Sebastien Konieczny, Pierre Marquis. "On Belief Promotion". The 16th International Conference on Principles of Knowledge Representation and Reasoning (KR'18), pages 297-306. Tempe, AZ, USA, October 2018.*

**c) Announcement discovering issues:**
We considered the problem of identifying the change formula in a belief revision scenario: given that an unknown announcement (a formula F) led a set of agents to revise their beliefs and given the prior beliefs and the revised beliefs of the agents, what can be said about F? We showed that under weak conditions about the rationality of the revision operators used by the agents, the set of candidate formulae has the form of a logical interval. We explained how the bounds of this interval can be tightened when the revision operators used by the agents are known and/or when F is known to be independent from a given set of variables. We also investigated the completeness issue, i.e., whether F can be exactly identified. We presented some sufficient conditions for it, identified its computational complexity, and reported the results of some experiments about it.

*Related publication:*
*- Nicolas Schwind, Katsumi Inoue, Sebastien Konieczny, Jean-Marie Lagniez, Pierre Marquis. "What Has Been Said? Identifying the Change Formula in a Belief Revision Scenario". The 28th International Joint Conference on Artificial Intelligence (IJCAI'19), pages 1865-1871. Macao, China, August 2019.*

**d) Computational issues:**
An appealing property of BRGs is that the belief sequence of each agent is always cyclic and

thus can be finitely characterized. However, identifying such belief cycles is a hard task. We addressed the computational issues and focused on the case where the revision policies of the agents are based on a well-known majority-based merging operator. In particular, we showed how some evolution patterns in the belief sequences can be identified independently of the propositional language used by the agents to express their beliefs, allowing an exhaustive search of all possible belief cycle patterns. By further identifying beliefs that lead to similar belief cycles, we introduced algorithms to reduce the search space and perform an exhaustive analysis of the dynamics of beliefs in any given network.

*Related publication:*

- *Gauvain Bourgne, Yutaro Totsuka, Nicolas Schwind, Katsumi Inoue. "Identifying Belief Sequences in a Network of Communicating Agents". The 22nd International Conference on Principles and Practice of Multi-Agent Systems (PRIMA'19), pages 370-386. Torino, Italy, October 2019.*

５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　3件）

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|---|---|
| １．著者名<br>Nicolas Schwind, Sebastien Konieczny, Pierre Marquis | ４．巻<br>- |
| ２．論文標題<br>On Belief Promotion | ５．発行年<br>2018年 |
| ３．雑誌名<br>The 16th International Conference on Principles of Knowledge Representation and Reasoning (KR'18) | ６．最初と最後の頁<br>297-306 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>なし | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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| １．著者名<br>Nicolas Schwind, Katsumi Inoue, Sebastien Konieczny, Pierre Marquis | ４．巻<br>- |
| ２．論文標題<br>What Has Been Said? Identifying the Change Formula in a Belief Revision Scenario | ５．発行年<br>2019年 |
| ３．雑誌名<br>The 28th International Joint Conference on Artificial Intelligence (IJCAI'19) | ６．最初と最後の頁<br>1865-1871 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>なし | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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| １．著者名<br>Nicolas Schwind, Pierre, Marquis | ４．巻<br>- |
| ２．論文標題<br>On Consensus in Belief Merging | ５．発行年<br>2018年 |
| ３．雑誌名<br>The 32nd AAAI Conference on Artificial Intelligence, New Orleans, Louisiana, USA, February 2-7, 2018 (AAAI'18) | ６．最初と最後の頁<br>1949-1956 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>なし | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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| １．著者名<br>Gauvain Bourge, Yutaro Totsuka, Nicolas Schwind, Katsumi Inoue | ４．巻<br>- |
| ２．論文標題<br>Identifying Belief Sequences in a Network of Communicating Agents | ５．発行年<br>2019年 |
| ３．雑誌名<br>The 22nd International Conference on Principles and Practice of Multi-Agent Systems (PRIMA'19) | ６．最初と最後の頁<br>370-386 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1007/978-3-030-33792-6_23 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>該当する |

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| 1．著者名<br>Nicolas Schwind, Sebastien Konieczny, Pierre Marquis | 4．巻<br>28(7) |
| 2．論文標題<br>Belief base rationalization for propositional merging | 5．発行年<br>2018年 |
| 3．雑誌名<br>Journal of Logic and Computation | 6．最初と最後の頁<br>1601-1634 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/logcom/exy029 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>該当する |

〔学会発表〕　計4件（うち招待講演　0件／うち国際学会　0件）

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| 1．発表者名<br>Nicolas Schwind |
| 2．発表標題<br>On Consensus in Belief Merging |
| 3．学会等名<br>The 32nd AAAI Conference on Artificial Intelligence, New Orleans, Louisiana, USA, February 2-7, 2018 (AAAI'18) |
| 4．発表年<br>2018年 |

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|---|
| 1．発表者名<br>Nicolas Schwind |
| 2．発表標題<br>On Belief Promotion |
| 3．学会等名<br>The 16th International Conference on Principles of Knowledge Representation and Reasoning (KR'18) |
| 4．発表年<br>2018年 |

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|---|
| 1．発表者名<br>Nicolas Schwind |
| 2．発表標題<br>What Has Been Said? Identifying the Change Formula in a Belief Revision Scenario |
| 3．学会等名<br>The 28th International Joint Conference on Artificial Intelligence (IJCAI'19) |
| 4．発表年<br>2019年 |

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| １．発表者名<br>Gauvain Bourgne |
| ２．発表標題<br>Identifying Belief Sequences in a Network of Communicating Agents |
| ３．学会等名<br>The 22nd International Conference on Principles and Practice of Multi-Agent Systems (PRIMA'19) |
| ４．発表年<br>2019年 |

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

| | 氏名<br>（ローマ字氏名）<br>（研究者番号） | 所属研究機関・部局・職<br>（機関番号） | 備考 |
|---|---|---|---|
| 研究協力者 | 井上　克巳<br><br>(Inoue Katsumi) | | |