様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）Synthesising directed structures in Computer Science using Directed Algebraic Topology

研究課題名（英文）Synthesising directed structures in Computer Science using Directed Algebraic Topology

研究代表者

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研究成果の概要（和文）：このプロジェクトの目標は、コンピューターサイエンス、数学、ロボット工学のさまざまな問題において、通常は時間の展開の影響によって、方向付けられた構造を記述および分析することでした。 このプロジェクト全体を通して、そしてフランスとドイツとの国内および国際的な協力のおかげで、私たちはこの目標に向けた理論とアルゴリズムを開発し、結果は国際会議やジャーナルで同時システムにすでに公開されており、ロボット工学と言語理論の準備につながっています。

研究成果の学術的意義や社会的意義
At this point of the project, the significance is mostly academic: the results obtained showed good theoretical results and algorithms in the analysis of directed structures.

研究成果の概要（英文）：The goal of this project was to describe and analyse directed structures, typically by the influence of the unrolling of time, in various problems in computer science, mathematics, and robotics. Throughout this project, and thanks to domestic and international collaborations with France and Germany, we have developed theories and algorithms towards this goal, with results already published for concurrent systems in international conferences and journal, and results in preparation for robotics and language theory.

研究分野：Foundation of mathematics

キーワード：algebraic topology　concurrency　language theory　robotics

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Directed algebraic topology is a mathematical domain initiated 20 years ago, to describe in a geometric and algebraic way, some information of distributed systems, that is, systems containing several components working ***at the same time*** and competing for resources (a typical example is a processor with several cores competing for memory). If some discrete semantics have been given to those systems using interleaving of traces, those do not allow components to ***truly*** work at the same time. True concurrency is tackling this problem by introducing a more continuous view of the semantics, which brings a topological and geometric flavor to the analysis of distributed systems.
It turned out that a crucial aspect of distributed systems was evading the scope of traditional tools from algebraic topology: the flow of time, by nature not reversible, was not compatible with the reversible structures of algebraic topology. Consequently, many mathematical tools were developed based on category theory to mimic those from classical algebraic topology, such as homology algebra, homotopy theory to incorporate the ***direction of time***.

２．研究の目的

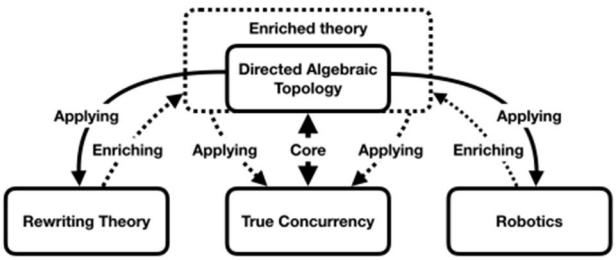
The original purpose of this proposal was to apply tools from directed algebraic topology to some specific problems in theoretical computer science. Homological and homotopical methods are particularly interesting, as they provide concise and computable algebraic invariants of the structures one is studying. Since the PI's thesis, such methods have been developed in a directed setting. It is natural to apply those new methods to problems where classical algebraic topology was applied, especially those that have an underlying directed structure, typically coming from an execution flow, time or an order, which are not handled by reversible structures.

３．研究の方法

The methodology for this project can be summarized by ***apply-and-enrich*** and consists in two inter-dependent steps.

1) <u>Apply Directed Algebraic Topology to Computer Science.</u>

This step is the main purpose described earlier. We want to apply the tools we have developed for true concurrency to other types of problems. The applications considered at the beginning of the project were: true concurrency (the original motivation), rewriting theory (and particularly the connection between homology and decidability of equational theories), robotics (and the notion of topological complexity of a planning problem), Homotopy Type Theory, and language theory (and the connection between semi-galois categories and coverings). To deal with that many different domains, collaborations with specialist in various backgrounds was needed, and this had been enabled by the present project (even though slowed by the pandemic), by starting and strengthening collaboration within Japan and abroad (mostly Europe).

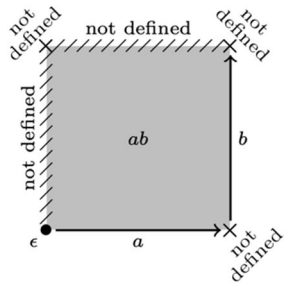


2) <u>Enrich Directed Algebraic Topology with new structures.</u>

The core of directed algebraic topology was developed around true concurrency, so the tools we have are mostly adapted to study truly concurrent systems. Applying the theory to more diverse problems would call for new structures that can enrich the whole theory. In turn, those new structures may be applied to the core of true concurrency or on other applications. This is made possible only thanks to the abstract language of category theory underlying the theory of directed algebraic topology, allowing the instantiation of abstract structure to different domains.

４．研究成果

1) **A new general model for true concurrency and its geometric interpretation.**



Higher Dimensional Automata are one of the first geometric models introduced in 1991 by Pratt. They successfully capture the essence of true concurrency but are not modular, in the sense that it is not easy to compose them. In this project, we introduced a new model, partial Higher Dimensional Automata which allow this modularity. This additional flexibility also allows us to describe an explicit relation with the theory of model structures in algebraic topology: the crucial notion of open maps in concurrency can be interpreted as fibrations in the language of model categories, for which trees and unfolding can be reformulated as cofibrant objects and cofibrant replacement.

2) **Comparison of abstract relations for concurrency.**

Open maps and coalgebra morphisms are two categorical ways of describing notions such as bisimulations, that is, behavioral equivalences between systems. The former has found new purposes in the theory of directed algebraic topology and true concurrency (see previous point, but also the PI's thesis), while the latter is widely used in Japan (in the group of the PI at the time) and abroad (mostly Europe). During a visit by Thorsten Wißmann from Germany, a collaboration was born to relate both notions, and the following was done: 1) proving that coalgebra morphisms can be described as open maps for non-deterministic systems, 2) extending open maps to deal with a wider range of systems (particularly probabilistic).

3) **Reachability analysis, with cofibrations.**

As a by-product of the previous point, a theory of reachability for systems described as coalgebras was developed, using the general theory of cofibrations. With the collaboration of Shin-ya Katsumata (a specialist in cofibrations), Thorsten Wißmann, and Stefan Milius from Germany (specialists in coalgebras), the general theory was designed and encapsulates various know algorithms with reachability flavor, such as, Dijkstra algorithm for shortest path, and Trajan algorithm for minimal spanning trees, and so on.

4) **Abstract language and Kleene theorems.**

At the occasion of several visits in Japan by (pre-pandemic, funded by the present project) and online meetings with (post-pandemic) Uli Fahrenberg from France, an international collaboration was developed to understand the language of Higher Dimensional Automata through the theory of coalgebras. Two challenges are being tackled: 1) describe HDA as coalgebras, 2) define the language of a coalgebra and prove that it can be succinctly described using regular expressions, like the Kleene theorem.

5) **Abstract effective systems.**

One drawback of those abstract general studies is that questions of effectiveness such as decidability and complexity are rarely considered. In this project, the PI made a proposal to migrate the theory of coalgebras from the usual setting of sets to the more general framework of topoi. Topoi objects are logically like sets, but they allow more diverse models, such as effective sets with computable functions, or even functions with a given complexity, thanks to realizability topoi. The PI proposed a way to extend the study of behavioral equivalences in this extended setting and is actively working on developing this line of work.

6) **Directed topological foundations for robotics.**

Based on the PI's thesis, Éric Goubault et al. (from France) proposed an extension of the topological complexity (a measure of how complex a planning problem in robotics can be) to a directed setting, in order to account for control constraints. Still some more foundations from directed algebraic topology are needed to work out the theory, and particularly, the PI together with Éric Goubault and Samuel Mimram are investigating categories enriched in topological spaces, a crucial concept in directed algebraic topology.

５．主な発表論文等

〔雑誌論文〕　計10件（うち査読付論文　10件／うち国際共著　10件／うちオープンアクセス　5件）

１．著者名 Sasinee Pruekprasert, Toru Takisaka, Clovis Eberhart, Ahmet Cetinkaya, and Jeremy Dubut	４．巻 -
２．論文標題 Moment Propagation of Discrete-Time Stochastic Polynomial Systems using Truncated Carleman Linearization	５．発行年 2020年
３．雑誌名 IFAC World Congress 2020	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Pruekprasert Sasinee, Clovis Eberhart, and Jeremy Dubut	４．巻 -
２．論文標題 Symbolic Self-triggered Control of Continuous-time Non-deterministic Systems without Stability Assumptions for 2-LTL Specifications	５．発行年 2020年
３．雑誌名 2020 16th International Conference on Control, Automation, Robotics and Vision (ICARCV)	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ICARCV50220.2020.9305387	査読の有無 有
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１．著者名 Jeremy Dubut	４．巻 12062
２．論文標題 Bisimilarity of Diagrams	５．発行年 2020年
３．雑誌名 RAMiCS 2020: Relational and Algebraic Methods in Computer Science	６．最初と最後の頁 65-81
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/978-3-030-43520-2_5	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Akihisa Yamada and Jeremy Dubut	４．巻 141
２．論文標題 Complete Non-Orders and Fixed Points	５．発行年 2019年
３．雑誌名 10th International Conference on Interactive Theorem Proving (ITP 2019)	６．最初と最後の頁 1-16
掲載論文のDOI（デジタルオブジェクト識別子） 10.4230/LIPIcs.ITP.2019.30	査読の有無 有
オープンアクセス 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 該当する

1．著者名 Sasinee Pruekprasert, Xiaoyi Zhang, Jeremy Dubut, Chao Huang and Masako Kishida	4．巻 -
2．論文標題 Decision Making for Autonomous Vehicles at Unsignalized Intersection in Presence of Malicious Vehicles	5．発行年 2019年
3．雑誌名 2019 IEEE Intelligent Transportation Systems Conference (ITSC)	6．最初と最後の頁 1-6
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ITSC.2019.8917132	査読の有無 有
オープンアクセス 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 該当する

1．著者名 Juraj Kolcak, Jeremy Dubut, Ichiro Hasuo, Shin-ya Katsumata, David Sprunger and Akihisa Yamada	4．巻 12078
2．論文標題 Relational Differential Dynamic Logic	5．発行年 2020年
3．雑誌名 TACAS 2020: Tools and Algorithms for the Construction and Analysis of Systems	6．最初と最後の頁 191-208
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/978-3-030-45190-5_11	査読の有無 有
オープンアクセス 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 該当する

1．著者名 Thorsten Wissmann, Stefan Milius, Shin-ya Katsumata, Jeremy Dubut	4．巻 60
2．論文標題 A coalgebraic view on reachability	5．発行年 2020年
3．雑誌名 Commentationes Mathematicae Universitatis Carolinae	6．最初と最後の頁 605～638
掲載論文のDOI（デジタルオブジェクト識別子） 10.14712/1213-7243.2019.026	査読の有無 有
オープンアクセス 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 該当する

1．著者名 Sprunger David, Katsumata Shin-ya, Dubut Jeremy, Hasuo Ichiro	4．巻 31
2．論文標題 Fibrational bisimulations and quantitative reasoning: Extended version	5．発行年 2021年
3．雑誌名 Journal of Logic and Computation	6．最初と最後の頁 1526～1559
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/logcom/exab051	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Dubut Jeremy, Yamada Akihisa	４．巻 Volume 18, Issue 1
２．論文標題 Fixed Points Theorems for Non-Transitive Relations	５．発行年 2022年
３．雑誌名 Logical Methods in Computer Science	６．最初と最後の頁 1--24
掲載論文のDOI（デジタルオブジェクト識別子） 10.46298/LMCS-18(1:30)2022	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Sasinee Pruekprasert, Clovis Eberhart, Jeremy Dubut	４．巻 -
２．論文標題 Fast Synthesis for Symbolic Self-triggered Control under Right-recursive LTL Specifications	５．発行年 2021年
３．雑誌名 2021 IEEE Conference on Decision and Control (CDC)	６．最初と最後の頁 1--8
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス 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 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）

１．発表者名 Jeremy Dubut
２．発表標題 Bisimilarity of Diagrams
３．学会等名 JSSST congress 2020
４．発表年 2020年

１．発表者名 Jeremy Dubut
２．発表標題 Bisimilarity of Diagrams
３．学会等名 RAMiCS 2020
４．発表年 2020年

１．発表者名 Jeremy Dubut
２．発表標題 Fixed Point Theorems for Non-Transitive Relations
３．学会等名 34th TRS meeting
４．発表年 2020年

１．発表者名 Jeremy Dubut
２．発表標題 Relational Differential Dynamic Logic
３．学会等名 Distributed and Hybrid System workshop
４．発表年 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 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関