RESEARCH CENTRE

Inria Centre at Université Côte d'Azur

IN PARTNERSHIP WITH:

CNRS, Université Côte d'Azur

2024
ACTIVITY REPORT

Project-Team
COATI

Combinatorics, Optimization and Algorithms for Telecommunications

IN COLLABORATION WITH: Laboratoire informatique, signaux systèmes de Sophia Antipolis (I3S)

DOMAIN

Networks, Systems and Services, Distributed Computing

THEME

Networks and Telecommunications

Inria

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Creation of the Project-Team: 2013 January 01

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Computer sciences and digital sciences

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1 Team members, visitors, external collaborators

Research Scientists

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- Amos Korman [University of Haifa, from Apr 2024 until Apr 2024, Professor]
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2 Overall objectives

COATI is a joint project-team gathering researchers from Inria, CNRS and Université Côte d'Azur. Its objectives are to conduct fundamental research in discrete mathematics, graph and digraph theory, algorithms design and operations research, and to use these knowledge and tools for addressing specific network optimization problems. Significant advances are made for instance on graph coloring problems, graph decomposition methods, combinatorial games on graphs, on the design and engineering of algorithms, etc. Furthermore, COATI addresses practical problems issued from telecommunication networks using tools from discrete mathematics and operations research in collaboration with industrial partners such as Orange labs, Nokia bell labs, Ciena, etc. We are particularly interested in optimization problems raised by the emergence of the new technologies of software defined networks (SDN) and network functions virtualization (NFV), and more specifically the placement and reconfiguration of lightpaths, network slices, service function chains, etc. We also consider the optimization of different kinds of wireless networks, including the design of reliable microwave backhaul networks, the deployment and management of fleets of drones to collect data from (mobile) sensors, and the optimization of the capacity of low power long range (LoRAWAN) networks.

During the last years, we have started to investigate how tools from artificial intelligence (AI), and in particular machine learning based methods, can help solving networks optimization problems, and how tools from (structural, metric) graph theory can help improving AI tools. More precisely, we have started to investigate the use of AI tools for networking problems, for instance for the reconfiguration of network slices in software defined networks or for the scheduling of machine learning tasks in heterogeneous clusters (Section 8.5). Furthermore, we have started to investigate the theory of deep learning, in particular by providing a rigorous understanding of some aspects of compression of artificial neural networks (Section 8.4). We have also started to investigate federated learning, for instance the privacy concern when implementing the learning algorithms in a network.

COATI also collaborates with teams in other domains (transport, biology, resource allocation, social sciences, etc.) to share its expertise for the resolution of various problems, as well as for identifying new optimization problems. Over the years, it has initiated fruitful collaborations in the fields of transport networks with SME Instant-System and Benomad (ANR Multimod 2018-2023) and with Amadeus, structural biology with project-team ABS, neurosciences with project-team CRONOS, and social sciences with SME MillionRoads and researchers from GREDEG and SKEMA.

The research done in COATI will result in the production of software components (proof of concepts) and to contributions to large open-source software such as Sagemath and packages of the Julia programming language eco-system. Finally, members of COATI are strongly involved in scientific mediation and will actively contribute to the development of Terra Numerica.

COATI has now reached the 12 years time limit for a project-team and a proposal for a new project-team (with the same name) is currently under evaluation.

3 Research program

Founded in 2013, COATI's goals are to conduct fundamental research in discrete mathematics, graph theory, digraph theory, algorithms and operations research, and to use these tools to study specific network optimization problems. Note that we are mainly interested in telecommunication networks. However, our expertise can be applied to solve many other problems in various fields (transport, biology, resource allocation, social sciences, etc.) and we collaborate with teams from these other fields. COATI also contributes to the development of software components to validate proposed algorithms and promote their dissemination.

The research program of COATI is therefore structured as follows.

- We conduct fundamental research in graph and digraph theory (Section 8.1). Our goal is to better understand the structure of (di)graphs and which particular (sub)structures make an optimization problem on (di)graphs difficult. We are particularly interested in digraphs which are less studied than (undirected) graphs, although most optimization problems are naturally modeled using digraphs. This is certainly due to the fact that several problems that can be solved in polynomial time on graphs are hard to solve on digraphs.

- We use this knowledge to design algorithms on (di)graphs (exact, sub-exponential, parameterized, approximation, heuristic) in order to solve various optimization problems (Section 8.2). We also study games on graphs as an algorithmic counterpart to some (di)graph theory studies, in order to gain more insight into problems and (di)graph properties. One of the challenges we face in designing algorithms is the increasing size of practical instances. Therefore, we need to find new ways of approaching problems using reduction and decomposition methods, characterizing polynomial instances (which are sometimes the practical ones), and designing algorithms with acceptable practical performance, independent of the worst-case time complexity, by exploiting some properties of the instances.
- Recently, we have begun to investigate how tools from graph theory and algorithms can help improve methods from machine learning (Section 8.4). For example, we have studied the problem of sparsifying neural networks and proved the strong lottery ticket hypothesis for convolutional neural networks. We have demonstrated the privacy vulnerability in federated graph learning and investigated methods to mitigate these risks through perturbation of the graph dataset.
- We study specific network optimization problems (Section 8.5) at both design and management levels such as energy efficiency in networks, routing reconfiguration of optical and software defined networks (SDN), placement and migration of virtual function chains (NFV), the deployment and management of fleets of drones to collect data from (mobile) sensors, the design of reliable wireless networks, the evolution of the routing in case of any type of topological modifications (maintenance operations, failures, capacity variations, ...), survivability to single and multiple failures, ... These specific problems often come from questions of our industrial partners (CIENA, Orange labs, Nokia). We first contribute to the modeling of these problems; then we either use existing tools or develop new tools in operations research and (di)graph theory to solve them.
- We also study optimization problems in other application areas such as structural biology, transport networks, economics, sociology, etc. For example, in the field of computational neuroscience, we have collaborated with the Inria project team CRONOS (Computational modeling of brain dynamical networks) from Sophia Antipolis. In the area of intelligent transport systems, we collaborate with the SMEs BeNomad and Instant-System on routing problems in multimodal transport systems. We also collaborate with GREDEG (Research Centre in Economics, Law and Management) and the SKEMA Business School to analyze the impact of competitive funding on the development of scientific networks. We have also investigated all and new Integrated Assessment Models for predicting the effect of policies on the Sustainable Development Goals by the United Nations.

  On the one hand, these collaborations benefit the concerned domains from the dissemination of our tools. On the other hand, they give rise to new problems of interest to our community, helping us to improve our knowledge and to test our algorithms on specific instances.
- We tackle problems in machine learning, multi-agent systems and computational neuroscience (Section 8.6). In machine learning, the work involves exploring the sparsification of artificial neural networks, particularly in relation to the Lottery Ticket Hypothesis and other machine learning challenges. In computational neuroscience, the research aims to develop algorithmic and mathematical tools to understand the organization of the central nervous system, addressing issues such as network alignment for brain atlases, modeling fMRI data, and interpreting brain activity. Our research on multi-agent systems is centered on computational dynamics, investigating distributed probabilistic algorithms for global coordination tasks. Significant contributions include rigorous analyses of consensus problems, along with applying theoretical insights to biological systems to understand collective animal behaviors.

The research done in COATI results in the production of prototype software and in the contribution to large open source software such as Sagemath and popular packages of the Julia programming language eco-system (Section 7.1).

Finally, besides our research activity, we are deeply involved in the dissemination of science towards a general audience and contribute actively to Terra Numerica (Section 10.3).

4 Application domains

COATI is mostly interested in telecommunications networks but also in the network structures appearing in social, molecular, and transportation networks.

4.1 Telecommunication networks

We focus on the design and management of heterogeneous physical and logical networks. The project has kept working on the design of backbone networks (optical networks, radio networks, IP networks). However, the fields of Software Defined Networks and Network Function Virtualization are growing in importance in our studies. In all these networks, we study routing algorithms and the evolution of the routing in case of any kind of topological modifications (maintenance operations, failures, capacity variations, etc.).

4.2 Other Domains

Our combinatorial tools may be well applied to solve many other problems in various areas (transport, biology, resource allocation, chemistry, smart-grids, speleology, etc.) and we collaborate with experts of some of these domains.

For instance, we collaborate with project-team ABS (Algorithms Biology Structure) from Sophia Antipolis on problems from Structural Biology and with project-team CRONOS on problems arising in computational neurosciences. We collaborate with SME MillionRoads since October 2019 on the modeling and exploration of the HumanRoads database that gathers more than 100 million curricula (studies and career paths of persons). Last, we collaborate with GREDEG (Groupe de Recherche en Droit, Economie et Gestion, Université Côte d'Azur) and the SKEMA business school on the analysis of the impact of competitive funding on the evolution of scientific collaboration networks.

5 Social and environmental responsibility

5.1 Footprint of research activities

Several COATI members are heavily involved in the sustainable development commission at the I3S laboratory. A citizens' convention on the laboratory's climate has been set up with 17 members chosen by lot. The aim is to consider transition scenarios and actions to reduce the laboratory's carbon footprint by 30% to 50% (the more the better) by 2030. They are discussing of proposals related to missions, daily transports and laboratory life. Reflecting on these actions within the laboratory enables a broader personal reflection on how to implement reduction actions in everyday life. A global reflection on the research thematics and how the researchers are evaluated will be carried on.

6 Highlights of the year

- Christelle Caillouet defended her habilitation thesis (HDR), entitled *Modélisation et Optimisation des réseaux sans fil: De l'usage des drones aux réseaux LoRaWAN* [62], on March 27, 2024.
- Emanuele Natale defended his habilitation thesis (HDR), entitled *Sur la somme de sous-ensembles aléatoires et quelques applications* [63], on March 20, 2024.

6.1 Awards

- Frédéric Giroire: 3IA Fellow since October 2024.

- Emanuele Natale: Chair 3IA junior since October 2024.
- Lucas Picasarri-Arrieta: second best PhD award in computer science 2024 of doctoral school ED STIC for his PhD entitled "*Digraph colouring*" [64], defended on June 18, 2024. He was supervised by Frédéric Havet.

7 New software, platforms, open data

7.1 New software

7.1.1 SageMath

Name: SageMath

Keywords: Combinatorics, Graph algorithmics, Number theory, Cryptography, Algebra

Scientific Description: SageMath is a free open-source mathematics software system. It builds on top of many existing open-source packages: NumPy, SciPy, matplotlib, Sympy, Maxima, GAP, FLINT, R and many more. Access their combined power through a common, Python-based language or directly via interfaces or wrappers.

Functional Description: SageMath is a free mathematics software system written in Python, combining a large number of mathematical libraries under a common interface.

INRIA teams contribute in different ways to the software collection. COATI adds new graph algorithms along with their documentations and contributes the improvement and maintenance of the graph module and its underlying data structures. LFANT contributes through libraries such as ARB and PARI/GP, and directly through SageMath code for algebras and ring and field extensions.

Release Contributions: See http://www.sagemath.org/changelogs/

News of the Year: We have pursued the maintenance of the graph module (fix bug, improve behavior, improve the performances of many methods). We have also added new methods such as the computation of the longest (induced) cycle, a uniform generator of random proper interval graphs, a method to enumerate cographs, etc.

URL: http://www.sagemath.org/

Contact: David Coudert

Participants: David Coudert, Xavier Caruso

7.1.2 WorldDynamics.jl

Name: WorldDynamics.jl

Keywords: Integrated assessment modeling, Scientific computing, Julia programming language

Scientific Description: The World Dynamics project aims to provide a modern framework to investigate integrated assessment models of sustainable development, based on current software engineering and scientific machine learning techniques. Our group is developing a Julia library to allow scientists to easily use and adapt different world models, from Meadows et al.'s World3 to recent proposals. By enabling an open, interdisciplinary, and consistent comparative approach to scientific model development, our goal is to inform global policy makers on environmental and economic issues.

Functional Description: Integrated Assessment Modeling is a research area that focuses on developing and applying integrated models of human and earth systems to help understand how key aspects of society may evolve in the future and how they might interact with the natural environment and with a changing climate.

Despite the importance of the field, there has been no general software framework which allows scientists to investigate integrated assessment models of sustainable development, by using and adapting the most famous world models, from Meadows et al.'s World3 to recent proposals.

WorldDynamics.jl is a new software library written by members of the COATI Team, that aims to fill such crucial gap, by providing a modern framework in the Julia programming language based on current software engineering and scientific machine learning techniques.

URL: https://github.com/worlddynamics/WorldDynamics.jl

Publication: hal-04117509

Contact: Emanuele Natale

Participants: Pierluigi Crescenzi, Paulo Bruno De Sousa Serafim, Aurora Rossi, Hicham Lesfari, Emanuele Natale

Partner: Gran Sasso Science Institute

7.1.3 Earth4All.jl

Name: Earth4All.jl

Keywords: Julia programming language, Integrated assessment modeling, Scientific computing

Functional Description: Integrated assessment models are critical tools for scientists to understand the complex interactions between human and natural systems, and for policymakers to design effective policies to address global social and environmental challenges. However, the lack of transparency and reproducibility of models hinders their use and confidence in their results. This software is an open source implementation of the recent Earth4All integrated assessment model in the Julia programming language, developed according to best coding practices using a modular modeling framework (WorldDynamics.jl), and is publicly available in a GitHub repository for community inspection and use under an open source license.

URL: https://github.com/worlddynamics/Earth4All.jl

Publication: hal-04780536

Contact: Emanuele Natale

Partner: Gran Sasso Science Institute

7.1.4 Idawi

Keyword: Middleware

Functional Description: Idawi is a middleware for the development and experimentation of distributed applications for multi-hop dynamic networks, like the IoT, the Edge, Mobile Ad hoc Networks, etc. The development of Idawi was initially motivated by the need of the COATI Research group to deploy scientific applications in clusters of computers, in order to run large experimentation campaigns of graph algorithms. Idawi is an innovative arrangement of many features found in existing tools into a fresh Open Source Java reference implementation, but in our Research context we were led to introduce new ideas not found in other middleware solutions for distributed computing - such as a fully decentralized network model, and a by-default collective communication/computation model (both naturally matching the very nature of mobile multi-hop networks), the use of digital twins at the core of its network management model, as well as new features making it usable as a Research platform for the experimentation of middleware-level techniques. Idawi defines application elements as components organized into a multi-hop overlay network on top of agnostic transport layers such as TCP, UDP and SSH (SSH being employed to enable component deployment and communication even in the presence of NATs and firewalls). In the usual use case, there will be only one component per device. But, in order to enable the simulation/emulation of large systems, components can deploy other components in their Java Virtual Machine (JVM) or in another JVM(s) in the same device. Idawi proposes a structuring model of distributed applications, which then must conform to a specific Object-Oriented model in the style of SOA: it defines that components expose their functionality via services. Services hold data and implement functionality about the specific concern they are about. Functionality is then exposed via (optionally typed) endpoints, which can be triggered remotely from anywhere in the component overlay. Idawi features a multi-paradigm programming model. Messaging (and hence remote code invocation) can be both synchronous (imperative) and asynchronous (reactive/event-driven). It is powered by a default routing scheme and APIs that are tailored to collective communication, so as to offer native support for parallel processing. Idawi comes with a set of built-in fully decentralized services for automatized quick deployment/bootstrapping of components through SSH, interoperability through a REST-based web interface, service provisioning and discovery, overlay management, and many other system-level functionality.

News of the Year: Improvement of the library and addition of new methods.

URL: https://github.com/lhogie/idawi

Publications: hal-04878642, hal-03863333, hal-03886521, hal-03562184

Contact: Luc Hogie

8 New results

8.1 Graph and digraph theory

COATI works mainly on two important topics in graph theory, namely graph colouring and directed graphs (digraphs), as well as on the interaction between the two. We study various substructure or partition problems in (di)graphs. For each of them, we aim at giving sufficient conditions that guarantee its existence and at determining the complexity of finding it. We aim to identify the similarities and differences between graphs and digraphs, both from structural and algorithmic perspectives. To this end, we investigate more or less systematically how some results on graphs, which can be reformulated as results on symmetric digraphs, can be generalized to digraphs.

Graph and digraph theory is a well-developed domain in the world. We are collaborating with many teams including almost all French groups in graph theory.

8.1.1 Structural graph and digraph theory

Participants: Frédéric Havet, Nicolas Nisse, Lucas Picasarri-Arrieta, Clément Rambaud.

One of our goals is to establish structural results on graphs and digraphs that can be used to design efficient algorithms. In particular, we are looking for substructures with certain properties or ways to represent or approximate efficiently graphs and digraphs.

Neighborhood complexity of planar graphs Reidl, Sánchez Villaamil, and Stravopoulos [98] characterized graph classes of bounded expansion as follows: A class $\mathscr{C}$ closed under subgraphs has bounded expansion if and only if there exists a function $f : \mathbb{N} \to \mathbb{N}$ such that for every graph $G \in \mathscr{C}$, every nonempty subset A of vertices in G and every nonnegative integer r, the number of distinct intersections between A and a ball of radius r in G is at most $f(r)|A|$. When $\mathscr{C}$ has bounded expansion, the function $f(r)$ coming from existing proofs is typically exponential. In the special case of planar graphs, it was conjectured by Sokołowski [100] that $f(r)$ could be taken to be a polynomial.

In [38], we prove this conjecture: For every nonempty subset A of vertices in a planar graph G and every nonnegative integer r, the number of distinct intersections between A and a ball of radius r in G

is $\mathcal{O}(r^4|A|)$. We also show that a polynomial bound holds more generally for every proper minor-closed class of graphs.

This is joint work with Gwenaël Joret *(Université Libre de Bruxelles)*.

Revisiting the Grid-Minor Theorem via treedepth We study the treedepth of graphs and its applications. The treedepth of a graph G can be defined as the minimum height of a Trémaux tree for a supergraph of G. Intuitively, where the treewidth of a graph measures how far it is from being a tree, this parameter measures how far a graph is from being a star.

In collaboration with Vida Dujmović *(University of Ottawa)*, Robert Hickingbotham *(Monash University)*, Jędrzej Hodor *(Jagiellonian University)*, Gwenaël Joret *(Université Libre de Bruxelles)*, Hoang La *(Jagiellonian University and Université Paris-Saclay)*, Piotr Micek *(Jagiellonian University)*, Pat Morin *(Carleton University)*, and David R. Wood *(Monash University)*, we give a qualitative strengthening of the celebrated Grid-Minor Theorem of Robertson and Seymour [99], in proving [50] that for every planar graph X of treedepth h, there exists a positive integer c such that for every X-minor-free graph G, there exists a graph H of treewidth at most $f(h)$ such that G is isomorphic to a subgraph of $H \boxtimes K_c$ (note that $H \boxtimes K_c$ is the graph obtained from H by 'blowing-up' each vertex of H by a complete graph K_c). We give three applications of this result: (1) improved upper bounds for the weak colouring numbers of graphs excluding a given minor, (2) an improved product structure theorem for apex-minor-free graphs, and (3) improved upper bounds for the p-centered chromatic number of graphs excluding a given minor.

Quickly excluding an apex-forest In [84], we give a short proof that for every apex-forest X on at least two vertices, graphs excluding X as a minor have layered pathwidth at most $2|V(X)|-3$. This improves upon a result by Dujmović, Eppstein, Joret, Morin, and Wood (SIDMA, 2020). Our main tool is a structural result about graphs excluding a forest as a rooted minor, which is of independent interest. We develop similar tools for treedepth and treewidth. We discuss implications for Erdős-Pósa properties of rooted models of minors in graphs.

This is joint work with Jędrzej Hodor *(Jagiellonian University)*, Hoang La *(Université Paris-Saclay)*, and Piotr Micek *(Jagiellonian University)*.

Blow-ups and extensions of trees in tournaments A class of acyclic digraphs $\mathscr{C}$ is linearly unavoidable if there exists a constant c such that every digraph $D \in \mathscr{C}$ is contained in all tournaments of order $c \cdot |V(D)|$. The class of all acyclic digraphs is not linearly avoidable, and Fox, He, and Wigderson recently showed that this is not even the case for acyclic digraphs with bounded maximum degree. On the positive side, Thomason and Häggkvist proved that the class of oriented trees is linearly unavoidable.

In collaboration with Pierre Aboulker and Raul Lopes *(DI-ENS, Paris)* and William Lochet *(LIRMM Montpellier)*, we generalize this result to acyclic digraphs obtained from an oriented tree by adding at most k vertices, and k-blow-ups of oriented trees, for every fixed integer k [65].

More precisely, we show that if D is obtained from an oriented tree F of order n by adding k universal vertices, then D is contained in every tournament of order $2 \cdot 3^{(k+1)(2k+1)} \cdot n$; and if D is obtained from F by replacing each vertex u by an independent set X_u of size k and every arc uv by all possible arcs from X_u to X_v, then D is contained in every tournament of order $2^{10+18k} k \cdot n$.

Complexity results on the decomposition of a digraph into directed linear forests and out-stars In collaboration with Florian Hörsch *(G-SCOP, Grenoble)*, we consider in [37] two decomposition problems in directed graphs. We say that a digraph is k-bounded for some $k \in \mathbb{Z}_{\geq 1}$ if each of its connected components contains at most k arcs.

For the first problem, a directed linear forest is a collection of vertex-disjoint directed paths and we consider the problem of decomposing a given digraph into a k-bounded and an ℓ-bounded directed linear forest for some fixed $k, \ell \in \mathbb{Z}_{\geq 1} \cup \{\infty\}$. We give a full dichotomy for this problem by showing that it can be solved in polynomial time if $k + \ell \leq 3$ and is NP-complete otherwise. This answers a question of Campbell, Hörsch, and Moore.

For the second problem, we say that an out-galaxy is a vertex-disjoint collection of out-stars. Again, we give a full dichotomy of when a given digraph can be arc-decomposed into a k-bounded and an

ℓ-bounded out-galaxy for fixed $k, \ell \in \mathbb{Z}_{\geq 1} \cup \{\infty\}$. More precisely, we show that the problem can be solved in polynomial time if $\min\{k, \ell\} \in \{1, \infty\}$ and is NP-complete otherwise.

8.1.2 Partitioning, colouring and labelling graphs and digraphs

Participants: Julien Bensmail, Frédéric Havet, Nicolas Nisse, Lucas Picasarri-Arrieta, Clément Rambaud.

Colourings in minor-closed graph classes A vertex colouring ϕ of a graph G is *p-centered* if for every connected subgraph H of G, either ϕ uses more than p colours on H, or there is a colour that appears exactly once on H. In [82], with Jędrzej Hodor *(Jagiellonian University)*, Hoang La *(Université Paris-Saclay)*, and Piotr Micek *(Jagiellonian University)*, we prove that for every fixed positive integer t, every K_t-minor-free graph admits a p-centered colouring using $\mathcal{O}(p^{t-1})$ colours. This improves upon the bound $\mathcal{O}(p^{d_t})$ for some non-explicit constant d_t proved by Piliczuk and Siebertz (JCTB, 2021). Moreover, for every fixed proper minor-closed class $\mathscr{C}$ of graphs, we determine the maximum p-centered chromatic number of a graph in G up to a factor in $\mathcal{O}(p \log p)$. This factor can be reduced to $\mathcal{O}(\log p)$ if $\mathscr{C}$ excludes a planar graph.

With the same researchers, we studied [83] the growth rate of weak colouring numbers of graphs excluding a fixed graph as a minor. Van den Heuvel et al. (European J. of Combinatorics, 2017) showed that for a fixed graph X, the maximum r-th weak colouring number wcol_r of X-minor-free graphs is polynomial in r. We determine this polynomial up to a factor of $\mathcal{O}(r \log r)$. Moreover, we tie the exponent of the polynomial to a structural property of X, namely, 2-treedepth. As a result, for a fixed graph X and an X-minor-free graph G, we show that $\mathrm{wcol}_r(G) = \mathcal{O}(r^{\mathrm{td}(X)-1} \log r)$, which improves on the bound $\mathrm{wcol}_r(G) = \mathcal{O}(r^{g(\mathrm{td}(X))})$ given by Dujmović et al. (SODA, 2024), where g is an exponential function. In the case of planar graphs of bounded treewidth, we show that the maximum r-th weak colouring number is in $\mathcal{O}(r^2 \log r)$, which is best possible.

Distinguishing labelling problems and the 1-2-3 Conjecture In distinguishing labelling problems, the general goal is, given a graph, to label some of its elements so that some pairs of elements can be distinguished according to some parameter computed from the labelling. Note that this description involves many parameters that can be played with, such as the set of elements to be labelled, the set of labels to be assigned, the set of elements to be distinguished, and the distinguishing parameter computed from the labelling. A notable example is the so-called 1-2-3 Conjecture, which asks whether almost all graphs can have their edges labelled with 1,2,3 so that every two adjacent vertices are distinguished accordingly to their sums of incident labels.

A proof of the 1-2-3 Conjecture has been provided recently, in 2024, by Keusch. Still, there are many related problems and questions of interest that are still open. In this context, our contribution, with Foivos Fioravantes *(Technical University in Prague, Czech Republic)*, Morgan Boivin, Hervé Hocquard, and Clara Marcille *(LaBRI, Université de Bordeaux, France)*, Igor Grzelec *(AGH University, Poland)*, and Mano Orenga *(ÉNS Lyon, France)*, is the following.

- In [28, 29], we have provided new results towards understanding better restrictions of the 1-2-3 Conjecture where only labels 1,2 can be assigned. In [28], we answered an open question, showing that there is no “easy” characterization of graphs that can be labelled this way while distinguishing neighbors via their incident multisets of labels but not via their incident sums of labels. In [29], we provided new results towards a conjecture stating that, assigning labels 1,2, we can generate “degenerate” incident sums, *i.e.*, there is no cycle of vertices having the same incident sum. Essentially, we proved this conjecture for classes of graphs larger than the ones for which the conjecture was known to hold.

- In [43, 70], we considered an equitable version of the 1-2-3 Conjecture, in which it is required that labels are assigned in a nearly equitable way. Essentially, in general, it was only known that, for a graph G, this can be achieved with labels $1, \ldots, |E(G)|$, while it is conjectured that we should always be able to achieve this with labels 1,2,3. We improved this best result by a factor 2, to $1, \ldots, |E(G)|/2$.

- In [26, 67], we considered three variants of the 1-2-3 Conjecture, namely the Weak, Standard, and Strong $(2,2)$-Conjectures, which, in brief, differ to the original conjecture in that we are now assigning coloured labels, resulting in several sums to play with for the vertices and to consider that neighbors are distinguished. In brief, the Weak variant is weaker than the original 1-2-3 Conjecture, while the Standard and Strong ones are stronger. Before the 1-2-3 Conjecture (and thus the Weak $(2,2)$-Conjecture) was proved, we proved the Weak $(2,2)$-Conjecture for more classes of graphs in [26], in which we were also the first ones to observe that this conjecture would be implied by the 1-2-3 Conjecture. In [67], we focused on the Strong $(2,2)$-Conjecture, which is widely open in general. We essentially proved this conjecture holds true for new classes of graphs, thereby supporting further the fact it might hold true.
- Finally, in [23, 68, 69], we introduced and studied new variants and problems related to the 1-2-3 Conjecture. In [23], we introduced a variant where resulting sums by a labelling must appear on about the same number of vertices (in an "equitable" way). In [69], we considered a variant in which labels cannot be assigned at will, and must result from an algorithmic process where vertices are "pushed". In [68], we introduced a stronger variant of so-called locally irregular decompositions, which are a useful notion that appeared in previous studies on the 1-2-3 Conjecture (essentially, in certain contexts, labelling a graph as desired is similar to decomposing it in a locally irregular way). For all these new problems we introduced, we provided first intuitions and stronger results, and raised sets of appealing problems and questions.

Directed colouring A *directed colouring* or *dicolouring* of a digraph is a colouring such that every colour class induces an acyclic digraph. The *dichromatic number* of a digraph D, denoted $\vec{\chi}(D)$. This is a natural generalization of (unidirected) graph colouring. Indeed, if G is an undirected graph, and D is the symmetric digraph obtained from G by replacing each edge with the pair of oppositely directed arcs joining the same pair of vertices, then $\chi(G) = \vec{\chi}(D)$.

- Generalizing colouring results to dicolouring.

  We first consider a fundamental result on graph colouring, namely Brooks' Theorem, which states that the chromatic number of a graph is almost always upper bounded by its maximal degree. Lovász showed that such a colouring may then be computed in linear time when it exists. Many analogues are known for variants of (di)graph colouring, notably for list-colouring and partitions into subgraphs with prescribed degeneracy. One of the most general results of this kind is due to Borodin, Kostochka, and Toft, when asking for classes of colours to satisfy "variable degeneracy" constraints. An extension of this result to digraphs has recently been proposed by Bang-Jensen, Schweser, and Stiebitz, by considering colourings as partitions into "variable weakly degenerate" subdigraphs. Unlike earlier variants, there existed no linear-time algorithm to produce colourings for these generalizations. In collaboration with Daniel Gonçalves and Amadeus Reinald *(LIRMM, Montpellier)*, we introduce the notion of (variable) *bidegeneracy* for digraphs, capturing multiple (di)graph degeneracy variants. We define the corresponding concept of F-dicolouring, where $F = (f_1,\dots,f_s)$ is a vector of functions, and an F-dicolouring requires vertices coloured i to induce a "strictly-f_i-bidegenerate" subdigraph. We prove in [79] an analogue of Brooks' theorem for F-dicolouring, generalizing the result of Bang-Jensen et al., and earlier analogues in turn. Our new approach provides a linear-time algorithm that, given a digraph D, either produces an F-dicolouring of D, or correctly certifies that none exist. This yields the first linear-time algorithms to compute (di)colourings corresponding to the aforementioned generalizations of Brooks' theorem. In turn, it gives an unified framework to compute such colourings for various intermediate generalizations of Brooks' theorem such as list-(di)colouring and partitioning into (variable) degenerate sub(di)graphs.

  The second statement that we studied is a famous conjecture of Reed asserting that every graph G satisfies $\chi(G) \le \lceil \frac{\Delta(G)+1+\omega(G)}{2} \rceil$. As a partial result, he proved the existence of $\epsilon > 0$ for which every graph G satisfies $\chi(G) \le \lceil (1-\epsilon)(\Delta(G)+1)+\epsilon\omega(G) \rceil$. In collaboration with Ken-Ichi Kawarabayashi *(NII and Univ. Tokyo, Japan)*, we propose an analogue conjecture for digraphs [53]. Given a digraph D, we denote by $\overleftrightarrow{\omega}(D)$ the size of a largest biclique (a set of vertices inducing a complete digraph) of D and $\tilde{\Delta}(D) = \max_{v\in V(D)} \sqrt{d^+(v)\cdot d^-(v)}$. We conjecture that every digraph D satisfies $\vec{\chi}(D) \le$

$\lceil \frac{\tilde{\Delta}(D)+1+\overleftrightarrow{\omega}(D)}{2} \rceil$, which if true implies Reed's conjecture. As a partial result, we prove the existence of $\epsilon > 0$ for which every digraph D satisfies $\overrightarrow{\chi}(D) \leq \lceil (1-\epsilon)(\tilde{\Delta}(D)+1) + \epsilon \overleftrightarrow{\omega}(D) \rceil$. This implies both Reed's result and an independent result of Harutyunyan and Mohar for oriented graphs.

- Dicolouring reconfiguration.

  In [30], we generalize several results on graph recolouring to digraphs. We first prove a complexity result : given two k-dicolourings of a digraph D, we prove that it is PSPACE-complete to decide whether we can transform one into the other by recolouring one vertex at each step while maintaining a dicolouring at any step even for $k = 2$ and for digraphs with maximum degree 5 or oriented planar graphs with maximum degree 6.

  We then study some conditions ensuring that a digraph has a k-dicolouring graph (the vertices of this graph are the k-dicolourings of the digraph and two are joined by an edge if the dicolourings differ only at one vertex) which is connected or which has bounded diameter.

  In particular, we pose as a conjecture that, for every digraph D, the dicolouring graph of D on $k \geq \delta^*_{\min}(D) + 2$ colours has diameter at most $O(|V(D)|^2)$, where $\delta^*_{\min}(D)$ is the min-degeneracy of D. This is the analogue of Cereceda's conjecture for digraphs. We generalize to digraphs two results supporting Cereceda's conjecture.

  Then, in collaboration with Ignasi Sau *(CNRS, LIRMM)* [39], we introduce a new parameter, called cycle-degeneracy, and use it to extend several evidences for Cereceda's conjecture to digraphs.

- Dicritical digraphs.

  A digraph is k-dicritical if $\overrightarrow{\chi}(D) = k$ and each proper subdigraph D' of D satisfies $\overrightarrow{\chi}(D') \leq k-1$. An oriented graph is a digraph with no directed cycle of length 2. For integers k and n, we denote by $o_k(n)$ the minimum number of edges of a k-dicritical oriented graph on n vertices. In collaboration with Pierre Aboulker *(École Normale Supérieure)* and Thomas Bellitto *(Sorbonne Université)*, we prove in [19] that $o_3(n) \geq \frac{7n+2}{3}$ together with a construction witnessing that $o_3(n) \leq \lceil \frac{5n}{2} \rceil$ for all $n \geq 12$. We also give a construction showing that for all sufficiently large n and all $k \geq 3$, $o_k(n) < (2k-3)n$, disproving a conjecture of Hoshino and Kawarabayashi.

  In [36], we prove that $o_4(n) \geq (\frac{10}{3} + \frac{1}{51})n - 1$ arcs. We also characterize the 4-dicritical digraphs on n vertices with exactly $\frac{10}{3}n - \frac{4}{3}$ arcs.

  In collaboration with Michael Stiebitz *(TU Ilmenau, Germany)*, we characterized in [41] the minimum number of arcs in k-critical digraphs with order at most $2k-1$. This generalizes a result about critical graphs obtained in 1963 by Tibor Gallai.

  In collaboration with Florian Hörsch *(G-SCOP, Grenoble)*, we give in [80] a human-readable proof that the collection of 3-dicritical semi-complete digraphs is finite. Further, we give a computer-assisted proof of a full characterization of 3-dicritical semi-complete digraphs. There are eight such digraphs, two of which are tournaments. We finally give a general upper bound on the maximum number of arcs in a 3-dicritical digraph.

  Aboulker et al. [93] proved that a digraph with large enough dichromatic number contains any fixed digraph as a subdivision. In [40], we give sufficient conditions on a dicritical digraph of large order or large directed girth to contain a given digraph as a subdivision. In particular, we prove that (i) for every integers k, ℓ, large enough dicritical digraphs with dichromatic number k contain an orientation of a cycle with at least ℓ vertices; (ii) there are functions f, g such that for every subdivision F^* of a digraph F, digraphs with directed girth at least $f(F^*)$ and dichromatic number at least $g(F)$ contain a subdivision of F^*, and if F is a tree, then $g(F) = |V(F)|$; (iii) there is a function f such that for every subdivision F^* of TT_3 (the transitive tournament on three vertices), digraphs with directed girth at least $f(F^*)$ and minimum out-degree at least 2 contain F^* as a subdivision.

Arbitrarily Partitionable Graphs In [21, 24, 25, 66], with Olivier Baudon, Morgan Boivin, and Lyn Vayssieres *(LaBRI, Université de Bordeaux, France)*, we pursued investigations on so-called arbitrarily partitionable (AP) graphs, being those graphs, answering a practical network sharing problem, that can be partitioned into arbitrarily many connected subgraphs with arbitrary orders. In [24, 25], we investigated several properties of AP graphs inspired by properties/results on Hamiltonian graphs, namely with respect to the notions of graph closure and triples of independent vertices, which have been commonly used in the literature to express sufficient conditions for graphs to be Hamiltonian. In [21, 66], we investigated other aspects of AP graphs, namely minimality properties (what can be said about AP graphs being not spanned by AP subgraphs?) and introduced a total variation (where both vertices and edges must be partitioned).

Colouring decorated graphs In [27], with Sandip Das *(Indian Statistical Institute, Kolkata, India)*, Soumen Nandi *(Netaji Subhas Open University, India)*, Ayan Nandy *(NIIT University, Neemrana, India)*, Théo Pierron *(LIRIS, Université Claude Bernard Lyon 1, France)*, Swathy Prabhu *(Ramakrishna Mission Vivekananda College (Autonomous), Chennai, India)*, and Sagnik Sen *(Indian Institute of Technology Dharwad, Dharwad, India)*, we introduced and initiated the study of a new type of colouring in oriented graphs, generalizing the notions of total-colouring and total chromatic number to oriented graphs. We provided first insights (properties, bounds, etc.) into the new chromatic parameter in question, in general and for several classes of particular oriented graphs.

On b-greedy colourings and z-colourings A b-greedy colouring is a colouring which is both a b-colouring and a greedy colouring. A z-colouring is a b-greedy colouring such that a b-vertex of the largest colour is adjacent to a b-vertex of every other colour. The b-Grundy number (resp. z-number) of a graph is the maximum number of colours in a b-greedy colouring (resp. z-colouring) of it. In collaboration with Jonas Costa Ferreira da Silva *(UFC Fortaleza, Brazil)*, we study in [32] those two parameters. We show that similarly to the z-number, the b-Grundy number is not monotone and can be arbitrarily smaller than the minimum of the Grundy number and the b-chromatic number. We also describe a polynomial-time algorithm that decides whether a given k-regular graph has b-Grundy number (resp. z-number) equal to $k+1$. We also prove that every cubic graph with no induced 4-cycle has b-Grundy number and z-number exactly 4.

8.1.3 Miscellaneous digraph problems

Participants: Frédéric Havet, Lucas Picasarri-Arrieta, Clément Rambaud.

Constrained Flows in Networks The support of a flow x in a network is the subdigraph induced by the arcs uv for which $x(uv) > 0$. In collaboration with Stéphane Bessy *(LIRMM, Montpellier)* and Joergen Bang-Jensen *(University of Southern Denmark, Odense)*, we discuss in [20] a number of results on flows in networks where we put certain restrictions on the structure of the support of the flow. Many of these problems are NP-hard because they generalize linkage problems for digraphs. For example deciding whether a network $\mathcal{N} = (D, s, t, c)$ has a maximum flow x such that the maximum out-degree of the support D_x of x is at most 2 is NP-complete as it contains the 2-linkage problem as a very special case. Another problem which is NP-complete for the same reason is that of computing the maximum flow we can send from s to t along p paths (called a maximum p-path-flow) in $\mathcal{N}$. Baier et al. (2005) gave a polynomial time algorithm which finds a p-path-flow x whose value is at least $\frac{2}{3}$ of the value of a optimum p-path-flow when $p \in \{2,3\}$, and at least $\frac{1}{2}$ when $p \geq 4$. When $p = 2$, they show that this is best possible unless P=NP. We show for each $p \geq 2$ that the value of a maximum p-path-flow cannot be approximated by any ratio larger than $\frac{9}{11}$, unless P=NP. We also consider a variant of the problem where the p paths must be disjoint. For this problem, we give an algorithm which gets within a factor $\frac{1}{H(p)}$ of the optimum solution, where $H(p)$ is the p'th harmonic number ($H(p) \sim \ln(p)$). We show that in the case where the network is acyclic, we can find such a maximum p-path-flow in polynomial time for every p. We determine the complexity of a number of related problems concerning the structure of flows. For the special case of acyclic digraphs, some of the results we obtain are in some sense best possible.

Diameter of the inversion graph In an oriented graph $\overrightarrow{G}$, the inversion of a subset X of vertices consists in reversing the orientation of all arcs with both endvertices in X. The inversion graph of a labelled graph

G, denoted by $\mathscr{I}(G)$, is the graph whose vertices are the labelled orientations of G in which two labelled orientations $\overrightarrow{G}_1$ and $\overrightarrow{G}_2$ of G are adjacent if and only if there is an inversion X transforming $\overrightarrow{G}_1$ into $\overrightarrow{G}_2$. In collaboration with Florian Hörsch *(CISPA Saarbrücken)*, we study in [81] the inversion diameter of a graph which is the diameter of its inversion graph denoted by $\mathrm{diam}(\mathscr{I}(G))$. We show that the inversion diameter is tied to the star chromatic number, the acyclic chromatic number and the oriented chromatic number. Thus a graph class has bounded inversion diameter if and only if it also has bounded star chromatic number, acyclic chromatic number and oriented chromatic number. We give some upper bounds on the inversion diameter of a graph G contained in one of the following graph classes: planar graphs ($\mathrm{diam}(\mathscr{I}(G)) \leq 12$), planar graphs of girth 8 ($\mathrm{diam}(\mathscr{I}(G)) \leq 3$), graphs with maximum degree Δ ($\mathrm{diam}(\mathscr{I}(G)) \leq 2\Delta - 1$), graphs with treewidth at mots t ($\mathrm{diam}(\mathscr{I}(G)) \leq 2t$). We also show that determining the inversion diameter of a given graph is NP-hard.

8.2 Graph algorithms

In the last years, COATI has conducted an intense research effort on the algorithmic aspects of graph theory. We are mainly interested in designing efficient algorithms for large graphs and in understanding how structural properties of networks can help for this purpose. In general, we try to find the most efficient algorithms, either exact algorithms or approximations, to solve various problems of graph theory, often with applications in telecommunication networks. We are involved in many international and national collaborations with academic and industrial partners.

We mainly focus on four topics: efficient computation of graph parameters, graph decompositions, combinatorial games in graphs, and distributed computing.

- We use graph theory to model various network problems. We study their complexity with the aim of identifying the key structural properties of graphs that make these problems hard or easy. We then search for the most efficient algorithms to solve the problems, sometimes focusing on specific graph classes from which the problems are polynomial-time solvable. Our algorithms are generally implemented (e.g., in Sagemath) and tested on real-life networks (e.g., road networks, Twitter, graph of co-publications from Scopus, etc.).
- Tree-decompositions are the corner-stone of many dynamic programming algorithms for solving graph problems. Since the complexity of such algorithms generally depends exponentially on the width (size of the bags) of the decomposition, much work has been devoted to compute tree-decompositions with small width. We propose different approaches, based on a pursuit-evasion perspective or on metric aspects of graphs, to compute optimal or approximate tree-decompositions of graphs.
- One important topic of COATI is the study of combinatorial games in graphs. For instance, we are strongly involved in the organization of GRASTA dedicated to pursuit-evasion games (and their relationships with tree-decompositions) and games in graphs (special issues [94, 96], organization of the 11^{th} edition of GRASTA in October 2023, etc.). We study combinatorial games for themselves by determining their complexity but also because they provide nice models for problems arising in telecommunication networks (e.g., localization games).
- Within the research area of the theory of distributed computing, COATI investigates the recent topics of computational dynamics on complex networks, namely the study of algorithmically-simple interaction rules among agents represented by nodes of a complex network. Such systems are of interest in many scientific areas, ranging from biology to sociology. We contribute to this research endeavour by focusing on the fundamental coordination problems, in which agents are required to agree on a configuration that satisfies some condition based on their initial input state.

8.2.1 Complexity of graph problems

Participants: Jean-Claude Bermond, Caroline Brosse, Michel Cosnard, David Coudert, Thomas Dissaux, Frédéric Havet, Nicolas Nisse, André Nusser, Lucas Picasarri-Arrieta.

Leanness Computation: Small Values and Special Graph Classes Let u and v be vertices in a connected graph $G = (V, E)$. For any integer k such that $0 \leq k \leq \mathrm{dist}_G(u, v)$, the k-*slice* $S_k(u, v)$ contains all vertices x on a shortest uv-path such that $\mathrm{dist}_G(u, x) = k$. The *leanness* of G is the maximum diameter of a slice. This metric graph invariant has been studied under different names, such as "interval thinness" and "fellow traveler property". Graphs with leanness equal to 0, a.k.a. *geodetic graphs*, have also received special attention in Graph Theory. The practical computation of leanness in real-life complex networks was studied recently (Mohammed et al., *COMPLEX NETWORKS*'21). In collaboration with Samuel Coulomb *(ENS Paris)* and Guillaume Ducoffe *(Univ. Bucharest, Romania)*, we give in [33] a finer-grained complexity analysis of two related problems, namely: deciding whether the leanness of a graph G is at most some small value ℓ; and computing the leanness on specific graph classes. We obtain improved algorithms in some cases, and time complexity lower bounds under plausible hypotheses.

New lower bounds on the cutwidth of graphs Cutwidth is a parameter used in many layout problems. Determining the cutwidth of a graph is an NP-complete problem, but it is possible to design efficient branch-and-bound algorithms if good lower bounds are available for cutting branches during exploration. Knowing how to quickly evaluate good bounds in each node of the search tree is therefore crucial.

In [72], we first answer the question of determining the maximum number of edges of any graph of order n and cutwidth C. We give a close formula and some upper bounds on independent interest. The main originality of this work is that its original motivation is to determine the maximum number of requests that can be groomed on a path network with bandwidth C.

Then we use this result in [71], to give new lower bounds based on different graph density parameters (minimum degree, degeneracy, maximum average degree, etc.). In particular, we give bounds using the notion of traffic grooming on a path network, which appear to be in many cases better than bounds in the literature. Furthermore, the bounds based on grooming can be computed quickly, in $O(\log n)$ time, and so are of interest to design faster branch-and-bound algorithms.

Dynamic connectivity in geometric intersection graphs A classical problem in computational geometry and graph algorithms is: given a dynamic set $\mathscr{S}$ of geometric shapes in the plane, efficiently maintain the connectivity of the intersection graph of $\mathscr{S}$. Previous papers studied the setting where, before the updates, the data structure receives some parameter P. Then, updates could insert and delete disks as long as at all times the disks have a diameter that lies in a fixed range $[\frac{1}{P}, 1]$. As a consequence of that prerequisite, the aspect ratio ψ (i.e. the ratio between the largest and smallest diameter) of the disks would at all times satisfy $\psi \leq P$. The state-of-the-art for storing disks in a dynamic connectivity data structure is a data structure that uses $O(Pn)$ space and that has amortized $O(P \log^4 n)$ expected amortized update time. Connectivity queries between disks are supported in $O(\log n / \log\log n)$ time.

In the dynamic setting, one wishes for a more flexible data structure in which disks of any diameter may arrive and leave, independent of their diameter, changing the aspect ratio freely. Ideally, the aspect ratio should merely be part of the analysis. Collaborating with Ivor van der Hoog and Eva Rotenberg *(Technical University of Denmark)*, and Frank Staals *(Utrecht University)*, we restrict our attention to axis-aligned squares, and study fully-dynamic square intersection graph connectivity in [51]. Our result is fully-adaptive to the aspect ratio, spending time proportional to the current aspect ratio ψ, as opposed to some previously given maximum P. Our focus on squares allows us to simplify and streamline the connectivity pipeline from previous work. When n is the number of squares and ψ is the aspect ratio after insertion (or before deletion), our data structure answers connectivity queries in $O(\log n / \log\log n)$ time. We can update connectivity information in $O(\psi \log^4 n + \log^6 n)$ amortized time. We also improve space usage from $O(P \cdot n \log n)$ to $O(n \log^3 n \log \psi)$ — while generalizing to a fully-adaptive aspect ratio — which yields a space usage that is near-linear in n for any polynomially bounded ψ.

Efficient enumeration of maximal split subgraphs and induced sub-cographs and related classes In collaboration with Aurélie Lagoutte *(G-SCOP, Univ. Grenoble Alpes, France)*, Vincent Limouzy and Lucas Pastor *(LIMOS, Univ. Clermont-Auvergne, France)* and Arnaud Mary *(LBBE, Univ. Claude Bernard-Lyon 1, France)*, we studied in [31] algorithms that take as input an arbitrary graph G, and that enumerate as outputs all the (inclusion-wise) maximal "subgraphs" of G which fulfill a given property Π. All over this paper, we study several different properties Π, and the notion of subgraph under consideration (induced or not) will vary from a result to another. More precisely, we present efficient algorithms to list all maximal split subgraphs, maximal induced cographs and maximal threshold graphs of a given input graph. All the algorithms presented here run in polynomial delay, and moreover for split graphs it only requires polynomial space. In order to develop an algorithm for maximal split (edge-)subgraphs, we establish a bijection between the maximal split subgraphs and the maximal stable sets of an auxiliary graph. For cographs and threshold graphs, the algorithms rely on a framework recently introduced by Conte & Uno (2019) called *Proximity Search*. Finally we consider the extension problem, which consists in deciding if there exists a maximal induced subgraph satisfying a property Π that contains a set of prescribed vertices and that avoids another set of vertices. We show that this problem is NP-complete for every non-trivial hereditary property Π. We extend the hardness result to some specific edge version of the extension problem.

8.2.2 Combinatorial games in graphs

Participants: Julien Bensmail, Jean-Claude Bermond, Michel Cosnard, Caroline Brosse, Frédéric Havet, Nicolas Almeida Martins, Nicolas Nisse.

Minimum lethal sets in grids and tori under 3-neighbor bootstrap percolation Let $r \geq 1$ be any non negative integer and let $G = (V, E)$ be any undirected graph in which a subset $D \subseteq V$ of vertices are initially *infected*. In collaboration with Fabricio Benevides *(UFC Fortaleza, Brazil)*, we consider in [22] the process in which, at every step, each non-infected vertex with at least r infected neighbors becomes infected and an infected vertex never becomes non-infected. The problem consists in determining the minimum size $s_r(G)$ of an initially infected vertices set D that eventually infects the whole graph G. This problem is closely related to cellular automata, to percolation problems and to the Game of Life studied by John Conway. Note that $s_1(G) = 1$ for any connected graph G. The case when G is the $n \times n$ grid, $G_{n\times n}$, and $r = 2$ is well known and appears in many puzzle books, in particular due to the elegant proof that shows that $s_2(G_{n\times n}) = n$ for all $n \in \mathbb{N}$. We study the cases of square grids, $G_{n\times n}$, and tori, $T_{n\times n}$, when $r \in \{3,4\}$. We show that $s_3(G_{n\times n}) = \lceil \frac{n^2+2n+4}{3} \rceil$ for every n even and that $\lceil \frac{n^2+2n}{3} \rceil \leq s_3(G_{n\times n}) \leq \lceil \frac{n^2+2n}{3} \rceil + 1$ for any n odd. When n is odd, we show that both bounds are reached, namely $s_3(G_{n\times n}) = \lceil \frac{n^2+2n}{3} \rceil$ if $n \equiv 5 \pmod 6$ or $n = 2^p - 1$ for any $p \in \mathbb{N}^*$, and $s_3(G_{n\times n}) = \lceil \frac{n^2+2n}{3} \rceil + 1$ if $n \in \{9, 13\}$. Finally, for all $n \in \mathbb{N}$, we give the exact expression of $s_3(T_{n\times n})$.

Convex set forming game In 1984, Frank Harary introduced the first graph convexity game, focused on the geodesic convexity. A set $S \subseteq V$ of vertices of a graph $G = (V, E)$ is convex if every shortest path between two vertices of S is also included in S. We introduce the Convex Set Forming Game : two players alternately select vertices in such a way that the set of selected vertices is always a convex set [73]. In the normal (resp., misère) variant, the last player to be able to select a vertex wins (resp., loses). We also define a new graph invariant $gc(G)$ as the largest integer k such that the first player has a strategy ensuring that, at the end of the game, at least k vertices of the graph G have been selected. We first show that the problems of deciding the outcome (does the first player win?) of the game in both variants (normal and misère), as well as the problem of deciding whether $gc(G) \geq k$, are PSPACE-complete. As a by-product, we prove that the optimization variant of the classical NODE KAYLES game is PSPACE-complete. Then, we focus on convexable graphs, i.e., n-node graphs G for which $gc(G) = n$. For this purpose, we say that a set $S = \{v_1, \cdots, v_{|S|}\} \subseteq V$ in a graph G admits a Convex Elimination Ordering (CEO) if $\{v_1, \cdots, v_i\}$ is convex for every $1 \leq i \leq |S|$. We show that the class of graphs whose vertex-set admits a CEO coincides with the chordal graphs and that this class strictly contains the convexable graphs. Moreover, every graph which is Ptolemaic (distance-hereditary chordal) or unit interval is convexable. Finally, we give a polynomial-time algorithm for computing a largest set admitting a CEO in outerplanar graphs, which gives upper bounds on $gc(G)$ in outerplanar graphs G.

This is a joint work with Nicolas Martins *(UNILAB - Universidade da Integração Internacional da Lusofonia Afro-Brasileira, Brazil)* and Rudini Sampaio *(UFC Fortaleza, Brazil)* in the context of the CANOE associated team.

Harmonious colouring game A harmonious k-colouring of a graph G is a 2-distance proper k-colouring of its vertices such that each edge is uniquely identified by the colours of its endpoints. Here, we introduce its game version: the harmonious colouring game [88]. In this two-player game, Alice and Bob alternately select an uncoloured vertex and assigns to it a colour in $\{1,\ldots,k\}$ with the constraint that, at every turn, the set of coloured vertices induces a valid partial harmonious colouring. Alice wins if all vertices are coloured; otherwise, Bob wins. The harmonious game chromatic number $\chi_{hg}(G)$ is the minimum integer k such that Alice has a winning strategy with k colours. In this paper, we prove the PSPACE-hardness of three variants of this game. As a by-product, we prove that a variant introduced by Chen et al. in 1997 of the classical graph colouring game is PSPACE-hard. We also obtain lower and upper bounds for $\chi_{hg}(G)$ in graph classes, such as paths, cycles, grids and forests of stars.

This is a joint work with Claudia Linhares Sales *(UFC Fortaleza, Brazil)*, Nicolas Martins *(UNILAB - Universidade da Integração Internacional da Lusofonia Afro-Brasileira, Brazil)* and Rudini Sampaio *(UFC Fortaleza, Brazil)* in the context of the CANOE associated team.

The Graph colouring Game in $4\times n$-Grids The graph colouring game is a famous two-player game (re)introduced by Bodlaender in 1991. Given a graph G and $k\in\mathbb{N}$, Alice and Bob alternately (starting with Alice) colour an uncoloured vertex with some colour in $\{1,\cdots,k\}$ such that no two adjacent vertices receive a same colour. If eventually all vertices are coloured, then Alice wins and Bob wins otherwise. The game chromatic number $\chi_g(G)$ is the smallest integer k such that Alice has a winning strategy with k colours in G. It has been recently (2020) shown that, given a graph G and $k\in\mathbb{N}$, deciding whether $\chi_g(G)\leq k$ is PSPACE-complete. Surprisingly, this parameter is not well understood even in "simple" graph classes. Let P_n denote the path with $n\geq 1$ vertices. For instance, in the case of Cartesian grids, it is easy to show that $\chi_g(P_m\square P_n)\leq 5$ since $\chi_g(G)\leq\Delta+1$ for any graph G with maximum degree Δ (here $\square$ denotes the Cartesian product of two graphs). However, the exact value is only known for small values of m, namely $\chi_g(P_1\square P_n)=3$, $\chi_g(P_2\square P_n)=4$ and $\chi_g(P_3\square P_n)=4$ for $n\geq 4$ [97]. In [74], we prove that, for every $n\geq 18$, $\chi_g(P_4\square P_n)=4$.

This is a joint work with Nicolas Martins *(UNILAB - Universidade da Integração Internacional da Lusofonia Afro-Brasileira, Brazil)* and Rudini Sampaio *(UFC Fortaleza, Brazil)* in the context of the CANOE associated team.

8.2.3 Algorithm engineering

Participants: David Coudert, Nicolas Nisse.

Algorithm Engineering is concerned with the design, analysis, implementation, tuning, and experimental evaluation of computer programs for solving algorithmic problems. It provides methodologies and tools for developing and engineering efficient algorithmic codes and aims at integrating and reinforcing traditional theoretical approaches for the design and analysis of algorithms and data structures. This approach is particularly suited when formal analysis pessimistically suggests bounds which are unlikely to appear on inputs of practical interest.

Practical Computation of Graph VC-Dimension For any set system $\mathcal{H}=(V,\mathcal{R})$, $\mathcal{R}\subseteq 2^V$, a subset $S\subseteq V$ is called *shattered* if every $S'\subseteq S$ results from the intersection of S with some set in $\mathcal{R}$. The *VC-dimension* of $\mathcal{H}$ is the size of a largest shattered set in V. In collaboration with Mónika Csikós *(IRIF Paris)*, Guillaume Ducoffe *(Univ. Bucharest, Romania)* and Laurent Viennot *(ARGO, Inria Paris)*, we studied in [46] the problem of computing the VC-dimension of graphs. In particular, given a graph $G=(V,E)$, the VC-dimension of G is defined as the VC-dimension of $(V,\mathcal{N})$, where $\mathcal{N}$ contains each subset of V that can be obtained as the closed neighborhood of some vertex $v\in V$ in G. Our main contribution is an algorithm for computing the VC-dimension of any graph, whose effectiveness is shown through experiments on various types of practical graphs, including graphs with millions of vertices. A key aspect of its efficiency resides in the fact that practical graphs have small VC-dimension, up to 8 in our experiments. As a side-product, we present several new bounds relating the graph VC-dimension to other classical graph theoretical notions. We also establish the $W[1]$-hardness of the graph VC-dimension problem by extending a previous result for arbitrary set systems.

Indexing Graphs for Shortest Beer Path Queries A *beer graph* is an edge-weighted graph $G = (V, E, \omega)$ with *beer vertices* $B \subseteq V$. A *beer path* between two vertices s and t of a beer graph is a path that connects s and t and visits at least one vertex in B. The *beer distance* between two vertices is the weight of a *shortest beer path*, i.e. a beer path having minimum total weight. A *graph indexing scheme* is a two-phase method that constructs an *index* data structure by a one-time preprocessing of an input graph and then exploits it to compute (or accelerate the computation of) answers to *queries* on structures of the graph dataset. In the last decade, such indexing schemes have been designed to perform, effectively, many relevant types of queries, e.g. on reachability, and have gained significant popularity in essentially all data-intensive application domains where large number of queries have to be routinely answered (e.g. journey planners), since they have been shown, through many experimental studies, to offer extremely low query times at the price of limited preprocessing time and space overheads.

In collaboration with Andrea d'Ascenzo *(LUISS Univ. Roma)* and Mattia d'Emidio *(GSSI L'Aquila)*, we show in [47] that an indexing scheme, to efficiently execute queries on beer distances or shortest beer paths for pairs of vertices of a beer graph, can be obtained by adapting the highway labeling, a recently introduced indexing method to accelerate the computation of classical shortest paths. We design a preprocessing algorithm to build a WHL index, i.e. a weighted highway labeling of a beer graph, and show how it can be queried to compute beer distances and shortest beer paths. Through extensive experimentation on real networks, we empirically demonstrate its practical effectiveness and superiority, in terms of offered trade-off between preprocessing time, space overhead and query time, with respect to the state-of-the-art.

8.3 Distributed algorithms

8.3.1 Complexity of distributed systems

Participants: Davide Ferré, Nicolas Nisse.

Weakly synchronous systems with three machines are Turing powerful Communicating finite-state machines (CFMs) are a Turing powerful model of asynchronous message-passing distributed systems. In weakly synchronous systems, processes communicate through phases in which messages are first sent and then received, for each process. Such systems enjoy a limited form of synchronization, and for some communication models this restriction is enough to make the reachability problem decidable. In particular, we explore the intriguing case of *p2p* (or FIFO) communication, where each ordered pair of machines (p2p) defines a dedicated first-in-first-out (FIFO) queue, for which the reachability problem is known to be undecidable for four processes, but decidable for two. In collaboration with Cinzia di Giusto and Étienne Lozes *(I3S, UniCA)*, we show in [59, 77, 78] that the configuration reachability problem for weakly synchronous systems of three processes is undecidable. This result is heavily inspired by our study on the treewidth of the Message Sequence Charts (MSCs) that might be generated by such systems. In this sense, the main contribution of this work is a weakly synchronous system with three processes that generates MSCs of arbitrarily large treewidth.

8.3.2 Opinion dynamics

Participants: Niccolo D'Archivio, Emanuele Natale.

Information spreading. Understanding how information can efficiently spread in distributed systems is a fundamental question in both biological research and artificial system design.

In collaboration with Robin Vacus *(Bocconi University)* in [48, 49], we address the self-stabilizing bit-dissemination problem, designed to capture the challenges of spreading information and reaching consensus among entities with minimal cognitive and communication capacities. Specifically, a group of n agents is required to adopt the correct opinion, initially held by a single informed individual, choosing from two possible opinions. In order to make decisions, agents are restricted to observing the opinions of a few randomly sampled agents, and lack the ability to communicate further and to identify the informed individual. Additionally, agents cannot retain any information from one round to the next. According to a recent publication by Becchetti et al. in SODA (2024), a logarithmic convergence time without memory is achievable in the parallel setting (where agents are updated simultaneously), as long as the number of samples is at least $\Omega(\sqrt{n \log n})$. However, determining the minimal sample size for an efficient protocol to exist remains a challenging open question. As a preliminary step towards an answer, we establish the first lower bound for this problem in the parallel setting. Specifically, we demonstrate that it is impossible for any memory-less protocol with constant sample size, to converge with high probability in less than an almost-linear number of rounds. This lower bound holds even when agents are aware of both the exact value of n and their own opinion, and encompasses various simple existing dynamics designed to achieve consensus. Beyond the bit-dissemination problem, our result sheds light on the convergence time of the "minority" dynamics, the counterpart of the well-known majority rule, whose chaotic behavior is yet to be fully understood despite the apparent simplicity of the algorithm.

The bit-dissemination problem become even more challenging when communication is affected by noise. When agents are able to control whom they interact with, noise can often be mitigated through redundancy or other coding techniques, but it may have fundamentally different consequences on well-mixed systems. Specifically, Boczkowski et al. (2018) considered the noisy $\mathcal{PULL}(h)$ model, where each message can be viewed as any other message with probability δ. The authors proved that in this model, the basic task of propagating a bit value from a single source to the whole population requires $\Omega(\frac{n\delta}{h(1-\delta|\Sigma|)^2})$ (parallel) rounds.

Our work [75] in collaboration with Amos Korman *(University of Haifa)* and Robin Vacus *(Bocconi University)* shows that the aforementioned lower bound is almost tight. In particular, when each agent observes all other agents in each round, which relates to scenarios where each agent senses the system's average tendency, information spreading can reliably be achieved in $\mathcal{O}(\log n)$ time, assuming constant noise. We present two simple and highly efficient protocols, thus suggesting their applicability to real-life scenarios. Notably, they also work in the presence of multiple conflicting sources and efficiently converge to their plurality opinion. The first protocol we present uses 1-bit messages but relies on a simultaneous wake-up assumption. By increasing the message size to 2 bits and removing the speedup in the information spreading time that may result from having multiple sources, we also present a simple and highly efficient self-stabilizing protocol that avoids the simultaneous wake-up requirement. Overall, our results demonstrate how, under stochastic communication, increasing the sample size can compensate for the lack of communication structure by linearly accelerating information spreading time.

8.4 Machine learning theory and algorithms

Participants: Francesco Diana, Davide Ferré, Frédéric Giroire, Emanuele Natale, Aurora Rossi, Chuan Xu.

In the last years, COATI has started investigating machine-learning-based methods to enhance algorithms or solve optimization problems in networks. It also investigates how to use tools from graph theory, algorithmic and combinatorics to improve machine-learning tools. We here present our last results in this direction.

8.4.1 New results on the Random Subset Sum problem and the Strong Lottery Ticket Hypothesis

Considerable research efforts have recently been made to show that a random neural network N contains subnetworks capable of accurately approximating any given neural network that is sufficiently smaller than N, without any training. This line of research, known as the Strong Lottery Ticket Hypothesis (SLTH), was originally motivated by the weaker Lottery Ticket Hypothesis, which states that a sufficiently large random neural network N contains *sparse* subnetworks that can be trained efficiently to achieve performances comparable to that of training the entire network N. Despite its original motivation, results on the SLTH have so far not provided any guarantee on the size of subnetworks. Such limitation is due to the nature of the main technical tool leveraged by these results, the Random Subset Sum (RSS) Problem. Informally, the RSS Problem asks how large a random i.i.d. sample Ω should be so that we are able to approximate any number in $[-1, 1]$, up to an error of ϵ, as the sum of a suitable subset of Ω.

In collaboration with Giordano Giambartolomei and Frederik Mallmann-Trenn *(King's College London, UK)*, we provide in [54] the first proof of the SLTH in classical settings, such as dense and equivariant networks, with guarantees on the sparsity of the subnetworks. Central to our results, is the proof of an essentially tight bound on the Random Fixed-Size Subset Sum Problem (RFSS), a variant of the RSS Problem in which we only ask for subsets of a given size, which is of independent interest.

8.4.2 Temporal graph neural networks.

We collaborated with Carlo Lucibello *(Bocconi University, Italy)* to contribute to the Julia open source libraries GraphNeuralNetworks.jl and MLDatasets.jl. Our project's objective was to extend the support of temporal graph neural networks in GraphNeuralNetworks.jl by creating several layers, known as temporal graph convolutional layers. These layers were designed specifically for a type of graph called `TemporalSnapshotsGNNGraph`. Particular emphasis was placed on layers combining graph convolutions with recurrent cells, using the Flux.jl machine learning framework as a reference for implementing the latter. Some implemented layers were the `DCRNN` layer for traffic prediction, the `GConvGRU` and `GConvLSTM` layers, and the `EGCN-O` layer for tasks such as node and edge classification as well as link prediction. Additionally, we adapted all the implemented temporal layers to work seamlessly with another Julia machine learning framework, Lux.jl, ensuring compatibility across frameworks. Beyond enhancing existing tools, we expanded the range of datasets available in MLDatasets.jl, a Julia package for machine learning datasets, by contributing new datasets. We restructured the repository into a multi-repository setup, created and deployed the multi-package documentation, as detailled in [90].

8.4.3 Attribute Inference Attacks for Federated Regression Tasks.

Federated Learning (FL) enables multiple clients, such as mobile phones and IoT devices, to collaboratively train a global machine learning model while keeping their data localized. However, recent studies have revealed that the training phase of FL is vulnerable to reconstruction attacks, such as attribute inference attacks (AIA), where adversaries exploit exchanged messages and auxiliary public information to uncover sensitive attributes of targeted clients. While these attacks have been extensively studied in the context of classification tasks, their impact on regression tasks remains largely unexplored. In [76], we address this gap by proposing novel model-based AIAs specifically designed for regression tasks in FL environments. Our approach considers scenarios where adversaries can either eavesdrop on exchanged messages or directly interfere with the training process. We benchmark our proposed attacks against state-of-the-art methods using real-world datasets. The results demonstrate a significant increase in reconstruction accuracy, particularly in heterogeneous client datasets, a common scenario in FL. The efficacy of our model-based AIAs makes them better candidates for empirically quantifying privacy leakage for federated regression tasks.

This work was done in collaboration with Othmane Marfoq *(Meta)*, Giovanni Neglia *(NEO)*, and Eoin Thomas *(Amadeus)*.

8.4.4 Link Inference Attacks in Vertical Federated Graph Learning.

Vertical Federated Graph Learning (VFGL) is a novel privacy-preserving technology that enables entities to collaborate on training Machine Learning (ML) models without exchanging their raw data. In VFGL, some of the entities hold a graph dataset capturing sensitive user relations, as in the case of social networks. This collaborative effort aims to leverage diverse features from each entity about shared users to enhance predictive models or recommendation systems, while safeguarding data privacy in the process. Despite these advantages, recent studies have revealed a critical vulnerability that appears in intermediate data representations, which may inadvertently expose link information in the graph. In [58], we propose a novel Link Inference Attack (LIA) that exploits gradients as a new source of link information leakage.

Assuming a semi-honest adversary, we demonstrate through extensive experiments on seven real-world datasets that our LIA outperforms state-of-the-art attacks, achieving over 10% higher Area Under the Curve in some instances, thereby highlighting a significant risk of link information leakage through gradients. We analytically derive our Label-based LIA's accuracy using graph characteristics, assessing target graph vulnerability.

This work was done in collaboration with Oualid Zari *(Eurecom)*, Ayşe Ünsal *(Eurecom)*, Melek Önen *(Eurecom)* and Javier Parra-Arnau *(Universitat Politècnica de Catalunya, Barcelona, Spain)*.

8.4.5 A Cautionary Tale: On the Role of Reference Data in Empirical Privacy Defenses

Within the realm of privacy-preserving machine learning, empirical privacy defenses have been proposed as a solution to achieve satisfactory levels of training data privacy without a significant drop in model utility. Most existing defenses against membership inference attacks assume access to reference data, defined as an additional dataset coming from the same (or a similar) underlying distribution as training data. Despite the common use of reference data, previous works are notably reticent about defining and evaluating reference data privacy. As gains in model utility and/or training data privacy may come at the expense of reference data privacy, it is essential that all three aspects are duly considered. In [52], we conduct the first comprehensive analysis of empirical privacy defenses. First, we examine the availability of reference data and its privacy treatment in previous works and demonstrate its necessity for fairly comparing defenses. Second, we propose a baseline defense that enables the utility-privacy tradeoff with respect to both training and reference data to be easily understood. Our method is formulated as an empirical risk minimization with a constraint on the generalization error, which, in practice, can be evaluated as a weighted empirical risk minimization (WERM) over the training and reference datasets. Although we conceived of WERM as a simple baseline, our experiments show that, surprisingly, it outperforms the most well-studied and current state-of-the-art empirical privacy defenses using reference data for nearly all relative privacy levels of reference and training data. Our investigation also reveals that these existing methods are unable to trade off reference data privacy for model utility and/or training data privacy, and thus fail to operate outside of the high reference data privacy case. Overall, our work highlights the need for a proper evaluation of the triad "model utility / training data privacy / reference data privacy" when comparing privacy defenses.

This work was done in collaboration with Caelin G. Kaplan *(NEO)*, Othmane Marfoq *(NEO)*, Giovanni Neglia *(NEO)*, and Anderson Santana de Oliveira *(NEO)*.

8.5 Network design and management

Participants: Christelle Caillouet, David Coudert, Frédéric Giroire, Frédéric Havet, Joanna Moulierac, Emanuele Natale, Stéphane Pérennes, Lucas Picasarri-Arrieta.

Network design is a very wide subject which concerns all kinds of networks. In telecommunications, networks can be either physical (backbone, access, wireless, ...) or virtual (logical). The objective is to design a network able to route a (given, estimated, dynamic, ...) traffic under some constraints (e.g. capacity) and with some quality-of-service (QoS) requirements. Usually, the traffic is expressed as a family of requests with parameters attached to them. In order to satisfy these requests, we need to find one (or many) paths between their end nodes. The set of paths is chosen according to the technology, the protocol or the QoS constraints. The last years have been very lively for networks which have seen the rises of several new paradigms, like Software Defined Networks (SDN) and Network Function Virtualization (NVF), of new technologies, like 5G or Elastic Optical Networks or LoRa, and of new usages, like Internet of Things or 5G or High quality video streaming. All these changes have brought or renewed a large number of algorithmic and optimization problems for the design and management of networks. In this context, our work has mainly focused on the study of three types of problems:

- How to build scalable routing solutions and reconfigure them without any interruptions for SDN?
- How to integrate and use AI for designing our solutions?

- How to efficiently route and place virtual resources in networks using NFV?
- How to use efficiently wireless networks?
- How to propose energy-efficient solutions?

This very wide topic is considered by a lot of academic and industrial teams in the world. Our approach is to tackle these problems with tools from operations research and discrete mathematics (some of them developed in our team, see Section 8.1 (Graph and Digraph Theory) and Section 8.2 (Algorithms and combinatorial optimization). This approach is shared by a number of other teams within Inria and worldwide, e.g. UFC and UNIFOR (Fortaleza, Brazil), Concordia Univ. (Montreal, Canada), Univ. Adolfo Ibanez (Santiago, Chile) with which we have direct collaboration.

8.5.1 Scheduling ML compressed models

With the advent and the growing usage of Machine Learning as a Service (MLaaS), cloud and network systems are now offering the possibility to deploy ML tasks on heterogeneous clusters. Then, network and cloud operators have to schedule these tasks, determining both when and on which devices to execute them. In parallel, several solutions, such as neural network compression, were proposed to build small models which can run on limited hardware. These solutions allow choosing the model size at inference time for any targeted processing time without having to re-train the network. In collaboration with Ramon Aparicio PArdo *(I3S, UniCA)*, we propose in [56, 57, 60] approximation algorithms with proven guarantees to solve a novel scheduling problem with task deadlines where the tasks can be compressed.

8.5.2 Enhancing Energy Efficient Task Caching and Offloading in Multi-Access Edge Computing

In recent years, Multi-Access Edge Computing (MEC) has emerged as a promising solution for enhancing energy efficiency in network applications. As a matter of fact, by offloading computational tasks to a server deployed near the base station and by caching both the outputs and the related code for completed tasks, it is possible to effectively reduce the energy consumption of mobile devices while ensuring adherence to their latency constraints. Although there have been some previous works on task caching and task offloading on the cloud, most of them focus on only one of these two strategies or formulate optimization problems that are hard to solve and propose a suboptimal solution.

In collaboration with Fabiano Lorusso *(I3S, UniCA)* and Guillaume Urvoy-Keller *(I3S, UniCA)*, we propose in [89] a linear model for the joint task caching and offloading optimization problem. Moreover, we present two efficient heuristics which provide close-to-optimal results in terms of energy efficiency with a low execution time. We further prove that the offloading sub-problem can be solved with an optimal algorithm. Finally, we demonstrate the performance and scalability of our propositions by extensive simulations on a large number of 100 000 mobile devices.

8.5.3 Optimizing Low Power Wide Area Networks

LoRa is a low-power and long range radio communication technology designed for low-power Internet of Things devices. LoRaWAN is a widely used wireless communication standard that enables the collection of measurement data from numerous monitoring applications (such as smart metering, pollution, and asset tracking). Most research work has been focused on the performance of LoRaWAN as a function of the uplink traffic, as this is the most common scenario. Nevertheless, downlink traffic is a fundamental building block of the LoRaWAN standard, and a crucial part of applications such as smart healthcare, where reliability is extremely important. In collaboration with Alexandre Guitton *(Université Clermont Auvergne)*, Oana Iova *(AGORA, Lyon)*, and Fabrice Valois *(AGORA, Lyon)*, we study in [44] the impact of the downlink traffic and different scheduling policies on the performance of LoRaWAN. We investigate: (i) the impact of an optimal schedule for the downlink traffic, (ii) the choice of the physical layer parameters used to send downlinks to end-devices during the second reception window, and (iii) the choice of the gateway that sends the downlinks. Our results show that even when using an optimal schedule, the presence of downlink traffic reduces the capacity of a LoRaWAN network up to 20%. The most limiting factor is the gateway, due to its duty cycle and half-duplex characteristics.

LoRaWAN mainly uses frequency bands for which network usage is limited to meet the requirements of mass deployment of several thousand connected objects. For example, in the European Union, a device cannot use frequency channels for more than 1% of the time in its duty cycle. This leads to a scheduling problem with waiting times. In collaboration with Teiki Rigaud *(ENS, Paris)*, we formalize in [45] the LoRaWAN data scheduling optimization problem with waiting times using linear programming. We derive an optimal algorithm for the special case of equivalent spreading factors (SF) and investigate approximation algorithms for specific and general cases. We finally discuss about the general problem's complexity.

8.6 Collaborations with other fields

One important objective of COATI is to use its expertise on graph algorithms and Operations Research to address problems in other scientific domains (transport, bio-informatics, e-health, ed-tech, etc.). During the last years, we have initiated several collaborations with academic and industrial partners in this direction. In this section, we present the last results we have obtained in the context of these collaborations. In addition, some results motivated by transportation networks are presented in Section 8.2.3.

We apply our expertise in combinatorics, graph theory and algorithms mainly to telecommunications networks. However, our knowledge can also be applied to other areas where graphs or networks occur. In particular, we have studied problems in social networks, neuroscience, world models, and transportation networks (discussed in the section 8.2). We push two interdisciplinary areas: Neuroscience and Social Networks for Social and Economic Sciences. For Neuroscience, we have relied on the expertise of local teams such as Inria project-team CRONOS and the NeuroMod thematic institute of the Université Côte d'Azur, which brings together 16 laboratories and 250 researchers and promotes interaction between the human sciences (psychology, behavioral economics, linguistics), modeling (computer science, mathematics, physics, etc.) and neurosciences (biology, neurophysiology, cognitive neuroscience, medicine, etc.). For social networks for social and economical science, we rely on the expertise of our collaborators from GREDEG (laboratory on law, economics and management in Sophia Antipolis) and the SKEMA business school. We are also in relationship with the Inria project-teams DIANA and ARGO, for their expertise in the measurements of social networks for the first one and in graph algorithms (e.g. clustering) and learning for networks for the second one. This interaction led to several works in an effort of finding good models for Twitter, based on the snapshot collected by DIANA. Last, part of this line of work is also somewhat opportunistic, i.e. we are seizing opportunities of collaborations that are presented to us by companies, Benomad and Instant-System for transportation networks and MillionRoads for social networks, which are in our area of expertise. These are good opportunities to apply our methods and tools to other use cases. For the project with MillionRoads, we also collaborated with Inria project-team WIMMICS.

8.6.1 Analysis of temporal brain networks

Participants: Emanuele Natale, Aurora Rossi.

Null models for temporal brain networks. In collaboration with Samuel Deslauriers-Gauthier *(CRONOS)*, we investigated the properties of temporal brain networks extracted from functional Magnetic Resonance Imaging (fMRI) data from the WU-Minn Human Connectome Project (HCP). We analyzed the networks focusing on temporal small-worldness. To test certain hypotheses of the observed functional connectivity, we proposed three temporal null models: the geometric euclidean model on a square and on a torus, and the hyperbolic geometric graph model. The hyperbolic model is popular in the research community for studying real-world complex networks. It can model both a high-tailed degree distribution and small-worldness. Our analysis indicates that the hyperbolic model is more effective in reproducing the small-worldness property of real data, making it a favorable null model [42].

Subnetwork contributions in narrative processing. Functional connectivity derived from functional Magnetic Resonance Imaging (fMRI) data has been increasingly used to study brain activity. We model brain dynamic functional connectivity during narrative tasks as a temporal brain network and employ a machine learning model to classify in a supervised setting the modality (audio, movie), the content (airport, restaurant situations) of narratives, and both combined. Leveraging Shapley values, we analyze subnetwork contributions within Yeo parcellations (7- and 17-subnetworks) to explore their involvement in narrative modality and comprehension [55, 91]. This work represents the first application of this approach to functional aspects of the brain, validated by existing literature, and provides novel insights at the whole-brain level. Our findings suggest that schematic representations in narratives may not depend solely on pre-existing knowledge of the top-down process to guide perception and understanding, but may also emerge from a bottom-up process driven by the ventral attention subnetwork.

This work has been done in collaboration with Yanis Aeschlimann *(CRONOS)*, Samuel Deslauriers-Gauthier *(CRONOS)*, , and Peter Ford Dominey *(INSERM UMR1093-CAPS, Université Bourgogne Franche-Comté, UFR des Sciences du Sport, Dijon, France)*.

8.6.2 Integrated Assessment Modeling

Participants: Emanuele Natale, Aurora Rossi.

An open-source framework written in Julia for integrated global assessment modeling. Trying to predict the evolution of human society in terms of its fundamental aspects is both a delicate and urgent issue for science. Over the years, a number of models have been developed to help in this respect. In [35, 92], we present WorldDynamics.jl, an open-source framework with the aim of enabling scientists to easily use and adapt different integrated assessment models for sustainable development. The library has been developed using the Julia programming language and incorporates different famous integrated assessment models. The implementation provided can directly benefit from a wide range of tools already available in the Julia language ecosystem, including the JuMP modeling language for performing mathematical optimization on aspects of the models. One of the integrated assessment models we implemented is the Earth for all (E4A) model [95]. It has been used to compare two different and opposite world development scenarios: the too little too late scenario, in which current policies are assumed to continue, and the giant leap (GL) scenario, in which 21 policies related to five turnarounds are identified to produce significant improvements in six indicators of human well-being. By using global and local sensitivity analyzes of the E4A model, we suggest that the evolution of the six indicators in the GL scenario can be approximately reached by focusing on just six policies and three turnarounds [34].

This work has been done in collaboration with Paulo Bruno Serafim, Lucia Nasti and Pierluigi Crescenzi *(Gran Sasso Science Institute, L'Aquila, Italy)*, and Giorgio Gambosi *(Dipartimento di Ingegneria dell'Impresa "Mario Lucertini", University of Rome "Tor Vergata", Rome, Italy)*.

9 Partnerships and cooperations

9.1 International initiatives

9.1.1 Inria associate team not involved in an IIL or an international program

CANOE

Participants: Christelle Caillouet, Frédéric Giroire, Frédéric Havet, Nicolas Nisse, Lucas Picasarri-Arrieta, Clément Rambaud.

Title: Combinatorial Algorithms for Networking prOblEms

Duration: 2023 - 2025

Coordinator: Nicolas Nisse

Partners: ParGO Research Group, Department of Mathematics, Federal University of Ceará, Fortaleza, Brazil

Summary: A graph is a mathematical structure that allows modeling networks in many contexts, from route networks, telecommunication networks, biological networks, neural networks to social networks. There are graph problems arising in each of these domains that are classified as computationally difficult, where the objective is to obtain an efficient algorithm for any graph presented as input. However, studying algorithms for a problem restricted to special graphs can shed light on the problem. This approach consists in assuming that the graph has some special structural property and exploiting this property in the algorithm. Such a structural property defines a class of graphs, such as trees or planar graphs. The aim is to build an efficient algorithm for a class of graphs, and then explore the ideas used to solve larger and larger classes of graphs or with fewer structural constraints. While a lot of work has been dedicated to the study of structural properties of graphs, very few results are known concerning directed graphs or hypergraphs which better model real-life networks. For instance, road networks are intrinsically directed and so are many social networks (e.g., Twitter), co-authorship networks correspond to hypergraphs (where each publication corresponds to an hyperedge gathering the co-authors), etc. This project aims at tackling challenging theoretical open problems in digraphs and/or hypergraphs. The purpose of this project is also to pursue and extend our fruitful collaboration with the ParGO team from Universidade Federal do Ceara (Fortaleza).

Web: team.inria.fr/coati/inria-associated-team-canoe/

9.1.2 Participation in other International Programs

CAPES-Cofecub project Ma 1004/23 : Graphs, Optimization, Combinatorics and Algorithms

Participants: Thomas Dissaux, Frédéric Giroire, Frédéric Havet, Nicolas Nisse, Lucas Picasarri-Arrieta, Clément Rambaud.

Title: Graphs, Optimization, Combinatorics and Algorithms

Duration: 2023 - 2026

Coordinator: Nicolas Nisse

Partners: ParGO Research Group, Department of Mathematics, Federal University of Ceará, Fortaleza, Brazil

Summary: Complementary project of the Inria EA CANOE.

9.2 International research visitors

9.2.1 Visits of international scientists

Other international visits to the team

- Hanneneh Akrami *(PhD at Max Planck Institute)*, January 29 - February 2, 2024.
- Jørgen Bang-Jensen *(Professor at the University of Southern Denmark)*, September 28-October 24, 2024.
- Lotte Blank *(PhD student at University of Bonn)*, October 14-18, 2024.
- Fabricio Benevides *(Professor at Universidade Federal do Ceará, Brazil)*, November 21-Decembre 4 2024.
- Nirupam Gupta *(Post-doc at EPFL, Switzerland)*, April 24 - May 5, 2024.

- Anatoly Khina *(Assistant Professor at Tel Aviv University, Israel)*, September 23 - October 10, 2024.
- Takako Kodate *(Lecturer at Tokyo Woman's Christian University, Japan)*, February 22 - March 3, 2024.
- Amos Korman *(Professor at University of Haifa)*, April 1-5, 2024.
- Vincent Limouzy *(Assistant Professor at LIMOS, Université Clermont Auvergne)*, March 25-29, 2024.
- Ana Karolinna Maia *(Assistant Professor at UFC Fortaleza, Brazil)*, until January 31, 2024.
- Frederick Mallmann-Trenn *(Senior Lecturer at King's College London)*, September 15-20, 2024.
- Rudini Menezes Sampaio *(Professor at UFC Fortaleza, Brazil)*, June 3-14, 2024.
- Malgorzata Sulkowska *(Assistant Professor at Univ. Wroclawski, Poland)*, April 25 - May 23, 2024.
- Robin Vacus *(Post-doc at Bocconi University, Italy)*, April 1-5, 2024.

9.2.2 Visits to international teams

Research stays abroad

- Christelle Caillouet: UFC, Fortaleza, Brazil (EA CANOE), October 20-31, 2024.
- Lucas Picasarri-Arrieta: NII Tokyo, Japan, March 18-April 6, 2024.
- Nicolas Nisse: UFC, Fortaleza, Brazil (EA CANOE), October 13-November 8, 2024.
- Clément Rambaud: Jagiellonian University, Kraków, Pologne. March 24 - April 28, 2024.
- Emanuele Natale: King's College London, London, United Kingdom. May 26 - June 14, 2024.
- Aurora Rossi: Birkbeck University, London, United Kingdom. May 26 - June 14, 2024.

9.3 European initiatives

9.3.1 Horizon Europe

HORIZON-CL4-2022-HUMAN-02-02 dAIEDGE, 2023-2026

Participants: Chuan Xu, Frédéric Giroire.

Program: HORIZON-CL4-2022-HUMAN-02-02 European Network of AI Excellence Centres: Expanding the European AI lighthouse.

Project acronym: dAIEDGE

Project title: A network of excellence for distributed, trustworthy, efficient and scalable AI at the Edge Granting Authority

Duration: September 2023 - August 2026

Coordinator: Alain Pagani *(DFKI)*

Other partners: 36 partners from 15 countries.

Summary: The dAIEDGE Network of Excellence (NoE) seeks to strengthen and support the development of a dynamic European cutting-edge AI ecosystem under the umbrella of the European Lighthouse for AI and to sustain the development of advanced AI.

dAIEDGE fosters the exchange of ideas, concepts, and trends on cutting-edge next generation AI, creating links between ecosystem actors to help both the European Commission (EC) and the European Union (EU) and the peripheral AI constituency identify strategies for future developments in Europe.

Our main objective is to advance Europe's innovation and technology base by developing a comprehensive policy and governance approach to AI in order for the EU to become a world leader in innovation in the data economy and its applications.

Web: daiedge.eu

9.4 National initiatives

DGA/Inria BioSwarm, 2013-2026

Participants: Niccolò D'Archivio, Emanuele Natale.

Program: DGA/Inria

Project acronym: BioSwarm

Project title: Bio-inspired algorithms for collective search and decision-making in drone swarms

Duration: 2023 - 2026

Coordinator: Emanuele Natale

Other partners: Inria EP CHROMA

Summary: The BioSwarm project focuses on decentralized algorithms inspired by the collective behavior of biological systems. It aims to enhance research strategies in unknown environments and improve collective decision-making through consensus among agents. The project will explore computational dynamics, particularly consensus algorithms that model decision-making processes observed in natural systems. It seeks to advance the understanding of how parameters, such as the majority threshold (k), influence the robustness and efficiency of consensus processes. Additionally, BioSwarm will investigate Lévy walks, a stochastic process relevant to collective behavior in multi-agent systems, through theoretical analyses and practical simulations.

ANR-19-CE48-0013 Digraphs, 2020-2024

Participants: Julien Bensmail, David Coudert, Frédéric Havet, Nicolas Nisse, Stéphane Pérennes.

Program: ANR

Project acronym: Digraphs

Project title: Digraphs

Duration: January 2020 - December 2024

Coordinator: Frédéric Havet

Other partners: LIRMM, Montpellier; LIP, Lyon

Summary: The objectives of the project are to make some advances on digraph theory in order to get a better understanding of important aspects of digraphs and to have more insight into the differences and the similarities between graphs and digraphs. Our methodology is two-fold. On the one hand, we will focus on the tools. Indeed we believe that many proof techniques have been too rarely used or adapted to digraphs and can be developed to obtain many more results. On the other hand, we will consider many results on graphs, find their (possibly many) formulations in terms of digraphs and see if and how they can be extended. Studying such extensions has been occasionally done, but the point here is to do it in a kind of systematic way. Moreover we shall push even further the study by considering classes of digraphs: if a result does not extend to the whole class of digraphs, for which classes does it extend ? If a result extends, can we get better results for some restricted classes of digraphs ?

Web: project.inria.fr/anrdigraphs/

Défi Inria-Cerema ROAD-AI, 2021-2024

Participants: Christelle Caillouet, David Coudert.

Project acronym: ROAD-AI

Project title: Routes et Ouvrages d'Art Diversiformes, Augmentés & intégrés

Duration: July 2021 - June 2024

Coordinators: Nathalie Mitton *(head, Inria, FUN)*, Christophe Biernacki *(vice-head, Inria, MODAL)*, Pierre Marchand *(CEREMA, DTEC ITM)*, André Orcési *(CEREMA, DTEC ITM)*

Inria participants: Inria project-teams ACENTAURI, COATI, FUN, MODAL, STATIFY, MODAL

Other partners: CEREMA

Summary: Integrated management of infrastructure assets is an approach which aims at reconciling long-term issues with short-term constraints and operational logic. The main objective is to enjoy more sustainable, safer and more resilient transport infrastructure through effective, efficient and responsible management. To achieve this, CEREMA and Inria are joining forces in this Inria Challenge (DEFI), whose main goals are to overcome scientific and technical barriers that lead to the asset management of tomorrow for the benefit of road operators: (i) build a "digital twin" of the road and its environment at the scale of a complete network; (ii) define "laws" of pavement behavior; (iii) instrument system-wide bridges and tunnels and use the data in real time; (iv) define methods for strategic planning of investments and maintenance.

Défi Inria Fed-Malin, 2022-2026

Participants: Francesco Diana, Frédéric Giroire, Chuan Xu.

Project acronym: Fed-Malin

Project title: Federated machine Learning over the internet

Duration: 2022 - 2026

Coordinators: Aurélien Bellet *(PREMEDICAL)*, Giovanni Neglia *(NEO)*

Inria participants: Inria project-teams ARGO, COATI, COMETE, EPIONE, MAGNET, MARACAS, NEO, SPIRALS, TRIBE, WIDE

Summary: In many use-cases of Machine Learning (ML), data is naturally decentralized: medical data is collected and stored by different hospitals, crowdsensed data is generated by personal devices, etc. Federated Learning (FL) has recently emerged as a novel paradigm where a set of entities with local datasets collaboratively train ML models while keeping their data decentralized. Fed-Malin is a research project that spans 10 Inria research teams and aims to push FL research and concrete use-cases through a multidisciplinary consortium involving expertise in ML, distributed systems, privacy and security, networks, and medicine. We propose to address a number of challenges that arise when FL is deployed over the Internet, including privacy & fairness, energy consumption, personalization, and location/time dependencies. Fed-Malin will also contribute to the development of open-source tools for FL experimentation and real-world deployments, and use them for concrete applications in medicine and crowdsensing.

Défi Inria-Hive Alvearium, 2022-2026

Participants: Frédéric Giroire, Stéphane Pérennes.

Project acronym: Alvearium

Project title: Large Scale Secure and Reliable Peer-to-Peer Cloud Storage: towards a shared sovereign cloud that respects its users' data

Duration: 2022 - 2026

Coordinator: Claudia-Lavinia Ignat

Inria participants: Inria project-teams COAST, COATI, MYRIADS, WIDE

Other partners: HIVE (www.hivenet.com)

Summary: The project aims to propose an alternative peer-to-peer cloud which provides both computing and data storage via a peer-to-peer network rather than from a centralized set of data centers. HIVE proposes to exploit the unused capacity of computers and to incentivize users to contribute their computer resources to the network in exchange for similar capacity from the network and/or monetary compensation. By exchanging similar computer resources and network capacity users can benefit from all cloud services. Peers store encrypted fragments of the data of other peers. This proposed peer-to-peer cloud solution addresses users concerns about the privacy of their data and the dependency on centralized cloud providers. In this collaboration with HIVE, we will apply our work on replication mechanisms for sharded encrypted data, data placement, Byzantine fault tolerance and security mechanisms in peer-to-peer environments.

Web: project.inria.fr/alvearium/

Défi Inria-Nokia LearnNet, 2024-2027

Participants: Frédéric Giroire, Chuan Xu.

Project acronym: LearnNet

Project title: Learning Networks

Duration: 2024 - 2027

Coordinator: Jean-Marie Gorce

Inria participants: Inria project-teams COATI, EPIONE, MARACAS, NEO, PREMEDICAL, STATIFY, TOTH and TRIBE

Other partners: Nokia

Summary: The LearnNet challenge explores new avenues of research at the intersection of the fields of networks and learning with two complementary objectives: rethinking the design of network protocols to serve machine learning applications, and exploring how learning can improve network management. Thus, the LearnNet challenge studies the growing entanglement between the challenges of large-scale learning and network design.

Web: www.inria.fr/en/learnnet

Défi Inria-Nokia SmartNet, 2024-2027

Participants: Frédéric Giroire, Joanna Moulierac.

Project acronym: SmartNet

Project title: AI Methods for Smart Network Management

Duration: 2024 - 2027

Coordinator: Yassine Hadjadj-Aoul

Inria participants: Inria project-teams COATI, ERMINE, NEO, SPADES and STACK

Other partners: Nokia

Summary: The challenge is dedicated to exploring the transformative potential of AI methods in enabling smart network management. The project strategically focuses on two key areas: slice provisioning and causal analysis of network malfunctions.

Web: www.inria.fr/en/smartnet

PEPR NF (Networks of the Future 2023-2030, 65M€)

Participants: Jamil Abou Ltaif, Yanis Achaichia, Christelle Caillouet, David Coudert, Frédéric Giroire, Joanna Moulierac.

Project acronym: NF

Project title: Networks of the Future

Duration: 2023 - 2030

Coordinators: Dmitri Kténas *(CEA)*, Serge Verdeyme *(CNRS)*, Daniel Koffman *(IMT)*

Inria participants: Inria project-teams AGORA, AIO, COATI, DIANA, DYOGENE, ERMINE, FUN, MARACAS, NEO, RESIST, TRIBE

Summary of PEPR NF: The 5G network and the networks of the future represent a key issue for French and European industry, society and digital sovereignty. This is why the French government has decided to launch a dedicated national strategy. One of this strategy's priority ambitions is to produce significant public research efforts so the national scientific community contributes fully to making progress that clearly responds to the challenges of 5G and the networks of the future. In this context, the CNRS, the CEA and the Institut Mines-Télécom (ITM) are co-leading the '5G' acceleration PEPR to support upstream research into the development of advanced technologies for 5G and the networks of the future.
Inria is involved into 8 research projects over the 10 supported by the program, with the participation of 11 project-teams of the theme "Networks and Telecommunications" and the coordination of the PC9-Founds.
COATI is involed in PC1 NF-MUST (End-to-end multi domain services management), coordinated by Djamal Zeghlache (IMT), which involves Inria project-teams COATI, DIANA and ERMINE.

PEPR Cloud, 2023-2030

Participants: Davide Ferré, Frédéric Giroire, Joanna Moulierac.

Project acronym: Cloud

Project title: Développement de technologies avancées de cloud

Duration: 2023 - 2030

Coordinators: CEA, INRIA

Inria participants: AVALON, COATI, SPIRALS

Summary: *PC CARECLoud - Understanding, improving, reducing the environmental impacts of Cloud Computing.*

Cloud computing and its many variations offer users considerable computing and storage capacities. The maturity of virtualization techniques has enabled the emergence of complex virtualized infrastructures, capable of rapidly deploying and reconfiguring virtual and elastic resources in increasingly distributed infrastructures. This resource management, transparent to users, gives the illusion of access to flexible, unlimited and almost immaterial resources. However, the power consumption of these clouds is very real and worrying, as are their overall greenhouse gas (GHG) emissions and the consumption of critical raw materials used in their manufacture. In a context where climate change is becoming more visible and impressive every year, with serious consequences for people and the planet, all sectors (transport, building, agriculture, industry, etc.) must contribute to the effort to reduce GHG emissions. Despite their ability to optimize processes in other sectors (transport, energy, agriculture), clouds are not immune to this observation: the increasing slope of their greenhouse gas emissions must be reversed, otherwise their potential benefits in other sectors will be erased. This is why the CARECloud project (understanding, improving, reducing the environmental impacts of Cloud Computing) aims to drastically reduce the environmental impacts of cloud infrastructures.

Cloud infrastructures are becoming more and more complex: both in width, with more and more distributed infrastructures, whose resources are scattered as close as possible to the user (edge, fog, continuum computing) and in depth, with an increasing software stacking between the hardware and the user's application (operating system, virtual machines, containers, orchestrators, microservices, etc.) The first objective of the project is to understand how these infrastructures consume energy in order to identify sources of waste and to design new models and metrics to qualify energy efficiency. The second objective focuses on the energy efficiency of cloud infrastructures, i.e., optimizing their consumption during the usage phase. In particular, this involves designing resource allocation and energy lever orchestration strategies: mechanisms that optimize energy consumption (sleep modes, dynamic adjustment of the size of virtual resources, optimization of processor frequency, etc.). Finally, the third objective targets digital sobriety in order to sustainably reduce the environmental impact of clouds. Indeed, current clouds offer high availability and very high fault tolerance, at the cost of significant energy expenditure, particularly due to redundancy and oversizing. This third objective aims to design infrastructures that are more energy and IT resource efficient, resilient to electrical intermittency, adaptable to the production of electricity from renewable energy sources and tolerant of the disconnection of a highly decentralized part of the infrastructure.

PEPR MOBIDEC - Mob Sci-Data Factory project, 2023-2030

Participants: David Coudert.

Project acronym: MOBIDEC

Project title: Digitalisation et décarbonation des mobilités

Duration: 2023 - 2030

Coordinators: IFP Energies nouvelles (IFPEN) and Université Gustave Eiffel (UGE)

Participants Mob Sci-Data Factory: INRIA (coordinator), UGE, IFPEN, IGN, CEREMA

Inria participants: AGORA, ASCII, COATI, FUN, TRIBE

Summary: The PEPR Data Technology for Mobility in the Territories (MOBIDEC) is in line with France 2030's objective of developing sober, sovereign and resilient mobility, by placing the collection, analysis and processing of mobility data at the heart of its work. It aims to understand and anticipate the mobility behaviors of goods and people, to facilitate the interpretation and processing of data, and to offer decision-making tools to simulate the impact of public policies in advance, or to assess the relevance of a new transport offer.

COATI is involed in project "Mob Sci-Data Factory", one of the three projects composing the PEPR MOBIDEC. It shares the PEPR's primary goal of contributing to developing more sustainable mobility strategies by providing decision-making support methodology and a digital toolbox fed by appropriately selecting and processing mobility data and by a deeper understanding of the involved transport uses and behaviors in mobility. It aims at clarifying and extracting the elements determining and explaining the characteristics of mobility data, which also raise the following challenging questions: (1) What data and what are their availability, accessibility, quality, and representativeness? (2) Which methods and digital tools are necessary for processing, calibrating, understanding, and enriching data while dealing with missing data and new acquisition ? (3) What are the specifications of the decision-support platform required for standard tools and data research sharing?

Mob Sci-Data Factory will make available in a secure and privacy-compliant cloud-based infrastructure different sources of mobility data together with open-source libraries and methods designed to be unified, modular, and interoperable from conception. Mob Sci-Dat Factory outcomes will facilitate data sovereignty and open-source development interoperability across multiple scientific actors in France, while accelerating research focused on mobility by offering privacy-compliant and secure data accessibility.

BPI SIRCAPASS, 2024-2028

Participants: Christelle Caillouet, David Coudert.

Project acronym: SIRCAPASS

Project title: Monitoring road infrastructure using passive sensors

Duration: 2024 - 2028

Coordinator: SilMach

Inria participants: Inria project-team FUN

Other partners: SilMach, AIA Ingénierie, CEREMA, with the support of Vinci Autoroutes

Summary: This project aims to provide an operational response to the challenges associated with the preventive monitoring of bridges and the planning of their maintenance. SIRCAPASS will propose an innovation that breaks with current practices and concepts, based on the use of energy-free sensors.

9.4.1 GDR Actions

GDR RSD, ongoing (since 2006) Members of COATI are involved in the working group RESCOM (*Réseaux de communications*) of GDR RSD of CNRS (gdr-rsd.cnrs.fr/). In particular, Christelle Caillouet is in the steering committee since July 2022.

We are also involved in the working group "Energy" of GDR RSD (gdr-rsd.fr/gt-energie). In particular, Frédéric Giroire is co-chair of this working group.

GDR IFM, ongoing (since 2006) Members of COATI are involved in the working group "Graphes" (gt-graphes.labri.fr/) and Complexité et algorithmes (CoA) www.gdr-ifm.fr/les-gt/gt-coa/ of GDR IM, CNRS. In particular, Frédéric Havet is member of the steering committee of the GT Graphes and Nicolas Nisse is member of the steering committee of the GT CoA.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: Steering Committees

- David Coudert :
  - member of the steering committee of the Symposium on Experimental Algorithms, since September 2022.
- Emanuele Natale :
  - member of the steering committee of the Symposium on Experimental Algorithms, since September 2022.
- Nicolas Nisse :
  - member of the steering committee of the Workshop on GRAph Searching, Theory and Applications (GRASTA), since 2014.

10.1.2 Scientific events: organisation

General chair, scientific chair

- Christelle Caillouet :
  - Co-chair of *Stream "Optimisation dans les réseaux de Télécom"* of ROADEF'24, Amiens, France, March 4-7, 2024

10.1.3 Scientific events: selection

Member of the conference program committees

- Christelle Caillouet :
  - IEEE WiMob: IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, Paris, France, October 21-23, 2024.
  - IEEE ISCC: IEEE Symposium on Computers and Communications, Paris, France, June 26-29, 2024.
  - AlgoTel: Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications, Saint-Briac-sur-Mer, France, May 27-31, 2024.
- David Coudert :

  - ATMOS: Symposium on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems, Amsterdam, Netherlands, September 7-8, 2023;
  - ESA - track B: European Symposium on Algorithms, Amsterdam, Netherlands, September 4-6, 2023;
  - IEEE ICC: IEEE International Conference on Communications, Rome, Italy, May 28 -June 1, 2023;
  - IEEE Globecom: IEEE Global Communications Conference, Kuala Lumpur, Malaysia, December 4-8, 2023;
  - ONDM: Conference on Optical Network Design and Management, Coimbra, Portugal, May 8-11 2023.

- Frédéric Havet :
  - JGA : 26ème Journées Graphes et Algorithmes, Dijon, France, November 19-22, 2024.
- Emanuele Natale :
  - AAAI Conference on Artificial Intelligence 2025
- André Nusser :
  - Latin American Theoretical Informatics (LATIN), March 18-22, 2024
  - European Symposium on Algorithms (ESA) Track B, September 2-4, 2024

10.1.4 Conferences

- Emanuele Natale:
  - Conference on Neural Information Processing Systems (NeurIPS) 2024
  - International Conference on Machine Learning (ICML) 24
- Chuan Xu:
  - International Conference on Learning Representations (ICLR) 2024

10.1.5 Journal

Member of the editorial boards

- Jean-Claude Bermond :
  - Computer Science Reviews (Elsevier);
  - Discrete Applied Mathematics (Elsevier);
  - Discrete Mathematics (Elsevier);
  - Discrete Mathematics, Algorithms and Applications (World Scientific);
  - Journal of Graph Theory (Wiley);
  - Advisory board of Journal of Interconnection Networks (World Scientific);
  - Networks (Wiley);
  - Parallel Processing Letters (World Scientific);
  - the SIAM book series on Discrete Mathematics (SIAM).
- Alexandre Caminada :
  - IEEE Transactions on Mobile Computing (IEEE);
  - IEEE Transactions on Vehicular Technology (IEEE);

  - Journal of Traffic and Transportation Engineering (Elsevier);
  - Sensors — Open Access Journal (MDPI);
  - Soft Computing (Springer).
- David Coudert :
  - Discrete Applied Mathematics (Elsevier);
  - Networks (Wiley).
- Frédéric Giroire :
  - Journal of Interconnection Networks (World Scientific);
- Frédéric Havet :
  - Discrete Mathematics and Theoretical Computer Science (DMTCS);
  - Innovations in Graph Theory
- Emanuele Natale :
  - The WikiJournal of Science (Wikimedia Foundation).
- Nicolas Nisse :
  - Discrete Applied Mathematics (Elsevier);
  - Special issue on "Theory and Applications of Graph Searching" of Theoretical Computer Science (Elsevier) [61].

10.1.6 Invited talks

- Julien Bensmail :
  - *Introducing and Extracting Irregularity in Graphs*. Journées Graphes et Algorithmes 2024 (JGA'24), Université de Bourgogne, November 2024.
- Frédéric Giroire:
  - *Opinion Dynamics*, Seminar of the D2S/Coord: Dependable Distributed Systems and Coordination Lab, Tokyo, Tokyo Tech, Japan, July 17, 2024.
  - *Scheduling with Fully Compressible Tasks: Application to Deep Learning Inference with Neural Network Compression*, Japan-France Joint Workshop 2024, NICT - National Institute of Information and Communications, July 10, 2024.
- Emanuele Natale:
  - *Algorithmic Principles in Neuroscience*, keynote at the 10th workshop on Biological Distributed Algorithms (BDA'24), Nantes, June 17, 2024. (slides)
  - *Trevisan's Contributions to Distributed Computing*, invited talk at the LucaFest Workshop at the Simons Institute for the Theory of Computing, Berkeley, USA, October 8, 2024. (slides)
  - *Dynamics and Community Structure in Networks*, invited talk at the Workshop on Computational Aspects of Complex Networks (CACN 2024), University of Rome Tor Vergata, Italy, December 6, 2024. (slides)
- Nicolas Nisse:
  - *On some positional games in graphs*. 11th Latin American Workshop on Cliques in Graphs (LAWCG), October 20-23, 2024, Fortaleza, Brazil.
- André Nusser:

  - *Approximating Klee's Measure Problem and a Lower Bound for Union Volume Estimation*, Geometry and Computing Workshop, October 21–25, 2024, CIRM, France.

- Aurora Rossi:
  - *Characterizing Dynamic Functional Connectivity Subnetwork Contributions in Narrative Classification with Shapley Values.* Invited Talk at the Department of Psychological Science, Birkbeck University, June 5, 2024 (slides).
  - *An Overview of Graph Neural Networks with GraphNeuralNetworks.jl.* Invited talk at the Julia and Optimization Days, October 8, 2024 (slides, gist).
  - *Que se passe-t-il dans le cerveau quand nous écoutons des histoires ?* Invited talk at M2AI 2024, November 28, 2024 (slides, video).

10.1.7 Leadership within the scientific community

- Christelle Caillouet :
  - Member of the steering committee of the GDR RSD and also chair of the Networking axis of the GDR RSD since July 2022.
  - Member of the mentorship actions committee of the GDR RSD.
- David Coudert :
  - Member of the steering committee of seminar Forum Numerica of Academy 1 RISE of UCA$^{\mathrm{JEDI}}$ since 2018;
- Frédéric Giroire :
  - Member of the steering committee of *GT Energy of the GDR RSD of CNRS.*
- Frédéric Havet :
  - Member of the steering committee of *GT Graphes of the GDR IFM of CNRS* since 2005;
  - Member of the Ramon Lull PhD prize committee (Spain).
- Joanna Moulierac :
  - Elected member of the "Conseil d'administration" of SPECIF CAMPUS (Société Professionnelle des Enseignants et Chercheurs en Informatique de France) since 2021.
- Nicolas Nisse :
  - Member of the steering committee of *GT CoA of the GDR IFM of CNRS* since 2018;
  - Member of the committee for the Ph.D. Prix "Charles Delorme" (GDR IFM, GT Graphe).

10.1.8 Scientific expertise

- Julien Bensmail :
  - External reviewer for the PRELUDIUM-23 program by the National Science Center (NSC) of Poland.
- Jean-Claude Bermond :
  - Expert for DRTT-MESR "Crédit impôt recherche" (CIR et agréments).
- Christelle Caillouet :
  - Member of the scientific advisory committee of the call for projects on « Intelligence Artificielle pour les futurs réseaux » of ANR « Thématiques Spécifiques en Intelligence Artificielle » (TSIA), June, 2024.

  - Member of the scientific committee for the best paper award of the national conference ROADEF 2024, February 2024.

- David Coudert :
  - Member of the Inria selection committe for “Action Exploratoire”, 2004;
  - Member of the scientific advisory committee of LIRMM (Montpellier, France), February 1-2, 2024.

- Frédéric Havet :
  - Expert for FNRS (Fonds de la recherche scientifique), Belgium

- Emanuele Natale :
  - Project reviewer for the Idées 2024 call of the Académie d’Excellence Réseaux, Information et Société numérique of Université Côte d’Azur, January-February 2024.

10.1.9 Research administration

- Christelle Caillouet :
  - Elected member of Conseil de Laboratoire I3S since 2017;

- Alexandre Caminada :
  - Member of the executive board of the Sophia Interdisciplinary Institute of Artificial Intelligence started in 2019;
  - Manager of the research committee for the Polytech network national academic Foundation.

- David Coudert :
  - Head of Science of the Inria Centre at Université Côte d’Azur, since September 2022;
  - Member of the “Bureau du comité des équipe-projets” of the Inria Centre at Université Côte d’Azur since 2018, head since September 2022;
  - Member of the Inria Evaluation Committee, since September 2022;
  - Member of the Inria committee for researchers promotions (CRHC, CRHC-8, DR1, DRCE, DRCE-2), 2024;
  - Member of the Inria selection committee for Senior Researchers (DR2), 2024;
  - Vice-President of the Inria selection committee for CRCN and ISFP in Sophia Antipolis, 2024;
  - Member of the Inria admission committee for ISFP in Sophia Antipolis, 2024;
  - Member of the Inria committee RIPEC C3, 2024.

- Frédéric Giroire :
  - Head of COMRED team of I3S laboratory, since April 2022;
  - In charge of the internships of stream UbiNet of Master 2 IFI, Université Côte d’Azur.

- Frédéric Havet :
  - Coordinator of ANR project Digraphs;
  - Co-head of Terra Numerica.

- Joanna Moulierac:
  - Member of the I3S CO2 group since 2019 (www.i3s.unice.fr/co2/);
  - Member of the CSPT Terra Numerica, since 2022.

- Emanuele Natale:
  - External member of University of Rome Tor Vergata's PhD School in Data Science (Italy).
- Nicolas Nisse :
  - Elected member for Inria at the CoSP of EUR DS4H since October 2020;
  - Nominated member for Inria at the board of doctoral school STIC, since September 2022;
  - Member of the "Comité de Suivi Doctoral" of Inria, since September 2022;
  - Member of the CSPT Terra Numerica, since 2020.
- Luc Hogie :
  - Elected member of Conseil de Laboratoire I3S.

10.2 Teaching - Supervision - Juries

10.2.1 Teaching responsibilities

- Julien Bensmail :
  - In charge of the whole course schedules of Département QLIO of IUT Nice Côte d'Azur.
- Christelle Caillouet :
  - Member of the "Conseil de Département Informatique" of IUT Nice Côte d'Azur (since September 2022).
  - "Directrice d'études" for the 1st-year students "en alternance" of "Département Informatique" of IUT Nice Côte d'Azur (since September 2024);
- Alexandre Caminada :
  - Head of the graduate school of engineering Polytech Nice Sophia (1500 master grade students, 100 faculty members, 50 staffs);
  - Member of the executive board of the Polytech network, national network of public graduate school of engineering;
  - Member of the executive board of Université Côte d'Azur.
- Joanna Moulierac :
  - Member of the "Conseil de Département Informatique" of IUT Nice Côte d'Azur (since September 2017).
- Michel Syska :
  - Head of the MIAGE (IT methods applied to business management) Master's degree MBDS (Mobiquity, Big Data and Systems integration), of Université Côte d'Azur (since September 2022);
  - Head of the Bachelor's degree in Artificial Intelligence (Licence Sciences et Technologies parcours IA), of Université Côte d'Azur;
  - Head of "Campus des Métiers et des Qualifications - Numérique", Université Côte d'Azur, Rectorat et Région PACA. See Section 10.3.1 for more details.

10.2.2 Teaching

Members of COATI have taught for more that **1200** hours (ETD) this year:

- PeiP: Clément Rambaud, *Programmation impérative*, 24h ETD, Level L1 (prépa), Polytech'Nice;
- BUT: Julien Bensmail, *Algorithmique et programmation avancées*, 64h ETD, Level L2, Département QLIO of IUT, Université Côte d'Azur, France;
- BUT: Julien Bensmail, *Amélioration des systèmes d'information*, 40h ETD, Level L3, Département QLIO of IUT Nice Côte d'Azur.
- BUT: Julien Bensmail, *Recherche Opérationnelle pour les systèmes de production*, 40h ETD, Level L3, Département QLIO of IUT Nice Côte d'Azur.
- BUT: Julien Bensmail, *Modélisation des systèmes d'information*, 40h ETD, Level L3, Département QLIO of IUT Nice Côte d'Azur.
- BUT: Julien Bensmail, *Fondamentaux de la Recherche Opérationnelle*, 40h ETD, Level L3, Département QLIO of IUT Nice Côte d'Azur.
- BUT: Julien Bensmail, *Bases de données*, 90h ETD, Level L2, Département QLIO of IUT Nice Côte d'Azur.
- BUT: Christelle Caillouet, *Automates et langages*, 12h ETD, Level L2, IUT, Université Côte d'Azur, France;
- BUT: Christelle Caillouet, *Programmation orientée objet*, 48h ETD, Level L1, IUT, Université Côte d'Azur, France;
- BUT: Christelle Caillouet, *Méthodes d'optimisation pour l'aide à la décision*, 21h ETD, Level L3, IUT, Université Côte d'Azur, France;
- BUT: Luc Hogie, *System programming*, 24h ETD, Level L2, IUT, Université Côte d'Azur, France;
- BUT: Joanna Moulierac, *Réseaux avancés*, 30h ETD, Level L2, IUT, Université Côte d'Azur, France;
- BUT: Lucas Picasarri-Arrieta, *Automates et langages*, 12h ETD, Level L2, IUT, Université Côte d'Azur, France;
- BUT: Lucas Picasarri-Arrieta, *Introduction à la programmation*, 52h ETD, Level L1, IUT, Université Côte d'Azur, France;
- BUT: Lucas Picasarri-Arrieta, *Méthodes d'optimisation pour l'aide à la décision*, 12h ETD, Level L1, IUT, Université Côte d'Azur, France;
- BUT: Lucas Picasarri-Arrieta, *Introduction aux Réseaux*, 40h ETD, Level L1, IUT, Université Côte d'Azur, France;
- Licence: Michel Syska, *Algorithmics*, 33h ETD, Level L3, parcours IA Science & Technologie - Université Côte d'Azur, France;
- Licence: Michel Syska, *Database systems*, 25h ETD, Level L3, MIAGE - Université Côte d'Azur, France;
- Licence: Michel Syska, *Heuristic search*, 21h ETD, Level L3, parcours IA Science & Technologie - Université Côte d'Azur, France;
- Licence: Pierre Pereira, *Base de l'IA*, 26h ETD, Level L3, parcours IA Science & Technologie - Université Côte d'Azur, France;
- Licence: Pierre Pereira, *Apprentissage*, 40h ETD, Level L3, parcours IA Science & Technologie - Université Côte d'Azur, France;

- Licence: Chuan Xu, *Programmation fonctionnelle*, 36h ETD, Level L3, Université Côte d'Azur, France;
- Licence: Chuan Xu, *Python pour l'IA*, 30h ETD, Level L3, - Université Côte d'Azur, France;
- Master: Christelle Caillouet, *Introduction Algorithmic and Programming*, 60h ETD, MAM3, Polytech Nice Sophia Antipolis, France;
- Master: Alexandre Caminada, *Radio location systems*, 20h ETD, Master 2 (in english), Polytech Nice Sophia Antipolis, France;
- Master: Alexandre Caminada, *Artificial intelligence*, 40h ETD, Master 2 (in english), Polytech Nice Sophia, France;
- Master: Alexandre Caminada, Master grade student's internship supervision and assesment, 10h ETD, Master 2, Polytech Nice Sophia Antipolis, France;
- Master: Frédéric Giroire, *Graph Algorithms*, 18h ETD, Master 2, International Track Ubinet, Université Côte d'Azur, France;
- Master: Frédéric Giroire, *Machine learning for networks*, 34.5 h ETD, Master 2, International Track Ubinet, Université Côte d'Azur, France;
- Master: Frédéric Giroire, *ICT and Environment, Green algorithm design*, 4.5h ETD, Master 2, minor, Université Côte d'Azur, France;
- Master: Nicolas Nisse, *Graphs*, 36h ETD, M1 Informatique et Interaction, Université Côte d'Azur, France;
- Master: Nicolas Nisse, *Algorithms for Telecoms*, 15h ETD, M2 Ubinet, Université Côte d'Azur, France;
- Master: Clément Rambaud, *Programmation en C++*, Polytech Nice, 16h ETD, 2nd year (M1), Engineer School, Polytech Nice.
- Master: Michel Syska, *Databases for big data*, 20h ETD, M1 MIAGE - Université Côte d'Azur, France;
- Master: Michel Syska, *Cloud computing*, 45h ETD, M2 MIAGE MBDS - Université Côte d'Azur, France.
- Master: Michel Syska, *Complex problem and heuristic search*, 27h ETD, M2 MIAGE IA2 - Université Côte d'Azur, France.
- Master: Chuan Xu, *Distributed-memory parallel programming and its applications*, 24h ETD, M1 Computer Science - Université Côte d'Azur, France.
- Master: Chuan Xu, *Federated Learning*, 24h ETD, M2 IF - Université Côte d'Azur, France.

10.2.3 Supervision

PhD thesis

- PhD in progress: Jamil Abou Ltaif, *Energy-efficient QoE-aware Beyond 5G Future Mobile Networks*, since November 2024. Co-supervisors: Chadi Barakat *(DIANA)*, Frédéric Giroire, Joanna Moulierac and Thierry Turletti *(DIANA)*;
- PhD in progress: Yanis Achaichia, *Optimizing the orchestration of virtualized services in a multi-domain environment*, since October 2024. Co-supervisors: Christelle Caillouet, Nicolas Huin *(IMT Atlantique)*, Géraldine Texier (IMT Atlantique);
- PhD in progress: Niccolò D'Archivio, *Bio-inspired algorithms for collective search and decision-making*, since April 2024. Co-supervisors: Emanuele Natale and Frédéric Giroire;

- PhD in progress: Tiago da Silva Barros, *Joint Training Design and Network Resource Allocation for Distributed Machine Learning*, since October 2022. Co-supervisors: Ramon Aparicio Pardo *(I3S, UniCA)* and Frédéric Giroire;
- PhD in progress: Francesco Diana, *Privacy Attacks in Federated Learning*, since January 2024. Co-supervisors: Chuan Xu and Giovanni Neglia *(NEO)*;
- PhD in progress: Davide Ferré, *Energy efficient deployment of applications in the edge-network-cloud continuum*, since January 2024. Co-supervisors: Frédéric Giroire and Emanuele Natale;
- PhD in progress: Henrique Lovisi Ennes, *Calcul quantique en topologie*, since October 2023. Co-supervisors: Clément Maria *(DATASHAPE)* and Nicolas Nisse;
- PhD in progress: Samuel Nascimento, *Convexity Games on Graphs*, PhD student in the Postgraduate Program in Computer Science at the Federal University of Ceará (UFC Fortaleza, Brazil) since March 2023, one year in France since November 2024. Supervisor : Rudini Menezes Sampaio *(UFC Fortaleza, Brazil)* and Nicolas Nisse;
- PhD in progress: Pierre Pereira, *Problem Size Generalization in Neural Combinatorial Optimization*, since October 2024. Co-supervisors: Emanuele Natale and Frédéric Giroire;
- PhD in progress: Clément Rambaud, *Colouring digraphs*, since September 2023. Supervisor: Frédéric Havet;
- PhD in progress: Aurora Rossi, *Algorithmic aspects and random network models for temporal brain networks*, since October 2022. Supervisor: David Coudert;
- PhD in progress: Caroline Aparecida de Paula Silva, *Universality and madericity of digraphs*, University of Campinas, Campinas, São Paulo, Brazil. Since September 1, 2024. Supervisor: Frédéric Havet;
- PhD: Lucas Picasarri-Arrieta *Digraph colouring* [64], June 18, 2024. Supervisor: Frédéric Havet.

Internships

- Licence: Martin Jouve-Genty, *Erdős-Pósa properties for small cycles in digraphs*. Licence 3, ENS Lyon, France, June 3 till July 12. Supervisors: Caroline Aparecida de Paula Silva, and Clément Rambaud.
- Google Summer of Code: Janmenjaya Panda, *Addition of the class of matching covered graphs in Sagemath*, IIT Madras, India, from May till November 2024. Mentor: David Coudert.
- Master 2: Fabiano Lorusso, *Energy-efficient Task caching and Offloading for Mobile Edge computing*, from March till August 2024. Co-supervisors : Frédéric Giroire, Joanna Moulierac, and Guillaume Urvoy-Keller *(I3S, UniCA)*.
- Master 2: Gabriele Cianni, *Evolution over time of the structure of social graphs*, from March till August 2024. Co-supervisors : Frédéric Giroire and Nicolas Nisse.
- Relai-thèse (to be followed by Phd) in progress: Rémi Godet, *Privacy on-demand and Security preserving Federated Generative Networks or Models*, since August 2024. Co-supervisors: Chuan Xu, Frédéric Giroire and Marco Lorenzi *(EPIONE)*.
- Relai-thèse (followed by Phd): Pierre Pereira, *Problem Size Generalization in NeuralCombinatorial Optimization*, May 1-August 31, 2024. Co-supervisors: Frédéric Giroire and Emanuele Natale;

Apprentices (for Terra Numerica)

- Vincent Chayé *(BUT Informatique, UniCA)*, since September 2023. Supervisor: Frédéric Havet.
- Hamadi Daghar *(Master 2 Informatique, UniCA)*, since September 2024. Supervisor: Nicolas Nisse.
- Destiny Hannah *(Master 1 MIAGE, UniCA)*, until August 2024. Supervisor: Joanna Moulierac.
- Mael Rivière *(Master 1 MIAGE, UniCA)*, since September 2024. Supervisor: Joanna Moulierac.

10.2.4 Juries

- Christelle Caillouet :
  - Referee and member of PhD committee of Simon Pichot, Toulouse INP, December 19, 2024;
  - Member of PhD committee of Gwendoline Hochet Derevianckine, INSA Lyon, December 17, 2024;
  - Member of PhD committee of Masoud Taghavian, IMT Atlantique, September 25, 2024;
  - Referee and member of PhD thesis of Dinesh Tamang, University of Pisa, Italy, June 20, 2024;
- Frédéric Giroire :
  - President of PhD committe of Younes Ben Mazziane, Centre Inria d'Université Côte d'Azur, équipe NEO, May 4, 2024;
  - President of PhD committe of Aymeric Picard Marchetto, Université Côte d'Azur, October 22, 2024;
- Frédéric Havet :
  - Referee and member of HDR committe of Edouard Bonnet, Ecole Normale Supérieure de Lyon, de Montpellier, April 15, 2024;
  - Referee and member of HDR committe of Alantha Newman, Grenoble Alpes Université, December 4, 2024;
- Emanuele Natale :
  - MSc thesis reviewer (2 thesis) for the MSc Modeling for Neuronal and Cognitive Systems at Université Côte d'Azur, 2024.
  - Jury member for the PhD scholarship selection of the Neuromod Institute, Université Côte d'Azur, 2024.
- Nicolas Nisse :
  - Member of Ph.D. committe of Mikhael Carmona, École Centrale Méditerranée, Marseille, December 20, 2024;
- Chuan Xu:
  - Member of Ph.D. committe of Fabiola Espinoza Castellon, Université Paris-Saclay, Paris, February 6, 2024

10.3 Popularization

10.3.1 Specific official responsibilities in science outreach structures

- Frédéric Havet is co-head of Terra Numerica and one of the person responsible of the "Comité Scientifique, Pédagogique et Technique" ; Nicolas Nisse is a member of this committee ; Joanna Moulierac is the referent of Terra Numerica for higher education ; Luc Hogie is in charge of hardware and software development.
- Frédéric Havet is member of the editorial board of *1024, le bulletin de la SIF (Société Informatique de France*, in which he draws cartoons to illustrate some articles.
- Michel Syska is Head of "Campus des Métiers et des Qualifications (CMQ)- Numérique" (Université Côte d'Azur, Rectorat et Région PACA). The CMQ brings together educational institutions to address national and regional economic needs in partnership with local authorities and businesses. In the PACA region, several studies reveal significant tension in digital professions. To address this gap, the PACA Digital CMQ aims to: 1) Make digital training programs more attractive, 2) Support the evolution of profession by offering comprehensive training opportunities across all qualification levels.

10.3.2 Productions (articles, videos, podcasts, serious games, ...)

Press articles related to Terra Numerica can be found at terra-numerica.org/presse/. Members of COATI have contributed to several of them.

10.3.3 Education

Most of the members of COATI are involved in Terra Numerica. During the year 2024, more than 300 events held, Terra Numerica has been visited by 290 classes (about 8000 primary school/college/highschool student, for 2 hours in average). We have trained about 360 persons (including 250 teachers) and touched more than 15000 people during events such as Fête de la science, etc.

10.3.4 Participation in Live events

Many members of COATI (Caroline Brosse, Michel Cosnard, Frédéric Giroire, Frédéric Havet, Joanna Moulierac, Nicolas Nisse, Lucas Picasarri-Arrieta, Stéphane Pérennes, Clément Rambaud, Michel Syska) participated some general audience science fairs, such as the Fête de la science in October 2024 (we were present on the "Village des Sciences" in Antibes-Juan-les-Pins, Valbonne, Villeneuve-Loubet, Vinon-sur Verdon) or some stages of the Science Tour Terra Numerica (20 days in several places : Digne-les-Bains, Forcalquier, Manosque, Aups, La Seyne sur Mer, Brignoles, Draguignan, Salernes, Roquebillière, Saint Martin de Vésubie, Breil sur Roya, Tende). They also occasionally act as scientific facilitator at Terra Numerica.

Frédéric Havet also gave general audience conferences in several cities (Bonson, Brignoles, Draguigan, Falicon, Menton, Rians, Vinon-sur-Verdon) as well as in for Esope 21, Science pour Tous 06, and Terra Numerica.

On November 28, 2024, Aurora Rossi delivered an invited talk titled *"Que se passe-t-il dans le cerveau quand nous écoutons des histoires ?"* during the Mois des Mathématiques Appliquées et Industrielles (M2AI) 2024 to an audience of 100 preparatory class students (BAC+1) and their teachers.

11 Scientific production

11.1 Major publications

[1] L. Becchetti, A. Clementi, E. Natale, F. Pasquale and L. Trevisan. 'Find Your Place: Simple Distributed Algorithms for Community Detection'. In: *SIAM Journal on Computing* 49.4 (Jan. 2020), pp. 821–864. DOI: 10.1137/19M1243026. URL: https://hal.science/hal-03025943.

[2] J. Bensmail, V. Campos, A. K. Maia, N. Nisse and A. Silva. 'Deciding the Erdős-Pósa property in 3-connected digraphs ⋆'. In: WG 2023 - 49th International Workshop on Graph-Theoretic Concepts in Computer Science. LNCS. Fribourg (CH), Switzerland, 28th June 2023. URL: https://inria.hal.science/hal-04084227.

[3] J. Bensmail, A. Harutyunyan, T.-N. Le and S. Thomassé. 'Edge-partitioning a graph into paths: beyond the Barát-Thomassen conjecture'. In: *Combinatorica* 39.2 (Apr. 2019), pp. 239–263. DOI: 10.1007/s00493-017-3661-5. URL: https://hal.archives-ouvertes.fr/hal-01744515.

[4] J.-C. Bermond, F. Giroire and N. Nisse. 'Graphes et Télécommunications'. In: *Bibliothèque Tangente*. Hors Serie 75 La recherche opérationnelle Hors Serie 75 (2021), pp. 120–125. URL: https://hal.archives-ouvertes.fr/hal-03455881.

[5] N. Bousquet, F. Havet, N. Nisse, L. Picasarri-Arrieta and A. Reinald. 'Digraph redicolouring'. In: *European Journal of Combinatorics* 116 (Feb. 2024), p. 103876. DOI: 10.1016/j.ejc.2023.103876. URL: https://hal.science/hal-04306893.

[6] C. Caillouet, F. Giroire and T. Razafindralambo. 'Efficient Data Collection and Tracking with Flying Drones'. In: *Ad Hoc Networks*. Ad Hoc Networks 89.C (2019), pp. 35–46. DOI: 10.1016/j.adhoc.2019.01.011. URL: https://hal.inria.fr/hal-02043136.

[7] N. Cohen, F. Havet, W. Lochet and N. Nisse. 'Subdivisions of oriented cycles in digraphs with large chromatic number'. In: *Journal of Graph Theory* 89.4 (Apr. 2018), pp. 439–456. DOI: 10.1002/jgt.22360. URL: https://hal.archives-ouvertes.fr/hal-01834779.

[8] D. Coudert, G. Ducoffe and N. Nisse. 'To Approximate Treewidth, Use Treelength!' In: *SIAM Journal on Discrete Mathematics* 30.3 (2016), p. 13. DOI: 10.1137/15M1034039. URL: https://hal.inria.fr/hal-01348965.

[9] D. Coudert, G. Ducoffe and A. Popa. 'P-FPT algorithms for bounded clique-width graphs'. In: *ACM Transactions on Algorithms* 15.3 (June 2019), pp. 1–57. DOI: 10.1145/3310228. URL: https://hal.archives-ouvertes.fr/hal-02152971.

[10] F. Dross and F. Havet. 'On the unavoidability of oriented trees'. In: *Journal of Combinatorial Theory, Series B* 151 (Nov. 2021), pp. 83–110. DOI: 10.1016/j.jctb.2021.06.003. URL: https://hal.inria.fr/hal-03269226.

[11] F. Giroire, F. Havet and J. Moulierac. 'On the Complexity of Compressing Two Dimensional Routing Tables with Order'. In: *Algorithmica* 80.1 (Jan. 2018), pp. 209–233. DOI: 10.1007/s00453-016-0243-7. URL: https://hal.inria.fr/hal-01686641.

[12] M. Heusse, T. Attia, C. Caillouet, F. Rousseau and A. Duda. 'Capacity of a LoRaWAN Cell'. In: *Proceedings of the 23rd International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM 2020)*. MSWiM '20. alicante, Spain: Association for Computing Machinery, Nov. 2020, pp. 131–140. DOI: 10.1145/3416010.3423228. URL: https://hal.archives-ouvertes.fr/hal-03010556.

[13] L. Hogie, M. Syska and N. Chleq. 'BigGraphs: distributed graph computing'. IDDN.FR.001.-410005.000.S.P.2015.000.31235 (France). 6th Sept. 2016. URL: https://hal.archives-ouvertes.fr/hal-01360649.

[14] H. Lesfari and F. Giroire. 'Nadege: When Graph Kernels meet Network Anomaly Detection'. In: IEEE International Conference on Computer Communications (INFOCOM). London, United Kingdom, 2nd May 2022. URL: https://hal.inria.fr/hal-03655867.

[15] W. Lochet. 'Immersion of transitive tournaments in digraphs with large minimum outdegree'. In: *Journal of Combinatorial Theory, Series B* (May 2018), p. 4. DOI: 10.1016/j.jctb.2018.05.004. URL: https://hal.archives-ouvertes.fr/hal-01835124.

[16] E. Natale, D. Ferre', G. Giambartolomei, F. Giroire and F. Mallmann-Trenn. 'On the Sparsity of the Strong Lottery Ticket Hypothesis'. In: *NeurIPS Proceedings*. NeurIPS 2024 - 38th Conference on Neural Information Processing Systems. Advances in Neural Information Processing Systems 37 (NeurIPS 2024). Vancouver, Canada, 10th Dec. 2024. URL: https://hal.science/hal-04741369.

[17] M. Rifai, N. Huin, C. Caillouet, F. Giroire, J. Moulierac, D. Lopez Pacheco and G. Urvoy-Keller. 'Minnie : An SDN world with few compressed forwarding rules'. In: *Computer Networks* 121 (July 2017), pp. 185–207. DOI: 10.1016/j.comnet.2017.04.026. URL: https://hal.inria.fr/hal-01576133.

[18] A. Rossi, S. Deslauriers-Gauthier and E. Natale. 'On null models for temporal small-worldness in brain dynamics'. In: *Network Neuroscience* (17th Jan. 2024), pp. 1–30. DOI: 10.1162/netn_a_00357. URL: https://hal.science/hal-04389639.

11.2 Publications of the year

International journals

[19] P. Aboulker, T. Bellitto, F. Havet and C. Rambaud. 'On the minimum number of arcs in k-dicritical oriented graphs'. In: *SIAM Journal on Discrete Mathematics* 38.2 (June 2024), pp. 1863–1901. DOI: 10.1137/23M1553753. URL: https://inria.hal.science/hal-04819231 (cit. on p. 13).

[20] J. Bang-Jensen, S. Bessy and L. Picasarri-Arrieta. 'Constrained Flows in Networks'. In: *Theoretical Computer Science* 1010 (27th Sept. 2024), p. 114702. DOI: 10.1016/j.tcs.2024.114702. URL: https://inria.hal.science/hal-04379871 (cit. on p. 14).

[21] O. Baudon, J. Bensmail and M. Boivin. 'Interplays between variations of arbitrarily partitionable graphs under minimality constraints'. In: *Applied Mathematics and Computation* 475 (2024), p. 128753. DOI: 10.1016/j.amc.2024.128753. URL: https://hal.science/hal-04260165 (cit. on pp. 13, 14).

[22] F. Benevides, J.-C. Bermond, H. Lesfari and N. Nisse. 'Minimum lethal sets in grids and tori under 3-neighbour bootstrap percolation'. In: *European Journal of Combinatorics* 119 (June 2024), p. 18. DOI: 10.1016/j.ejc.2023.103801. URL: https://inria.hal.science/hal-04368240 (cit. on p. 17).

[23] J. Bensmail. 'A notion of vertex equitability for proper labellings'. In: *Discrete Applied Mathematics* 346 (2024), pp. 228–247. DOI: 10.1016/j.dam.2023.12.014. URL: https://hal.science/hal-04012367 (cit. on p. 12).

[24] J. Bensmail. 'A $\sigma 3$ condition for arbitrarily partitionable graphs'. In: *Discussiones Mathematicae Graph Theory* 44.2 (2024), pp. 755–776. DOI: 10.7151/dmgt.2471. URL: https://hal.science/hal-03665116 (cit. on p. 13).

[25] J. Bensmail. 'Closure Results for Arbitrarily Partitionable Graphs'. In: *Opuscula Mathematica* 44.6 (2024), pp. 773–788. URL: https://hal.science/hal-04370225 (cit. on p. 13).

[26] J. Bensmail. 'On a graph labelling conjecture involving coloured labels'. In: *Discussiones Mathematicae Graph Theory* 44.1 (2024), pp. 231–244. DOI: 10.7151/dmgt.2441. URL: https://hal.science/hal-02554102 (cit. on p. 12).

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