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IN PARTNERSHIP WITH:

CNRS, Université Côte d'Azur

2022

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

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Project-Team COATI

Creation of the Project-Team: 2013 January 01

Keywords

Computer sciences and digital sciences

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A1.2.3. – Routing

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B7.2. – Smart travel

B9.5.1. – Computer science

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2 Overall objectives

COATI is a joint team between the Inria Centre at Université Côte d'Azur and the I3S laboratory (Informatique Signaux et Systèmes de Sophia Antipolis) which itself belongs to CNRS (Centre National de la Recherche Scientifique) and Université Côte d'Azur. Its research fields are Algorithmics, Discrete Mathematics, and Combinatorial Optimization, with applications mainly in telecommunication networks.

The main objectives of the COATI project-team are to design networks and communication algorithms. In order to meet these objectives, the team studies various theoretical problems in Discrete Mathematics, Graph Theory, Algorithmics, and Operations Research and develops applied techniques and tools, especially for Combinatorial Optimization and Computer Simulation. In particular, COATI used in the last years both these theoretical and applied tools for the design of various networks, such as SDN (software defined networks), WDM, wireless (radio), satellite, and peer-to-peer networks. This research has been done within various industrial and international collaborations.

COATI also investigates other application areas such as bio-informatics and transportation networks.

The research done in COATI results in the production of prototypes and more advanced software, and in the contribution to large open source software such as Sagemath.

3 Research program

Since its creation in 2013, the objectives of COATI are to conduct fundamental research in Discrete Mathematics, Graph Theory, Digraph Theory, Algorithms and Operations Research, and to use these tools for studying specific network optimization problems. Notice that we are mostly interested in telecommunications networks. However, our expertise can be applied to solve many other problems in various areas (transport, biology, resource allocation, social sciences, smart-grids, speleology, etc.) and we collaborate with teams of these other domains. COATI also contributes to the development of software components in order to validate proposed algorithms and to boost their dissemination.

The research program of COATI is therefore structured as follows.

- We conduct fundamental research in graph and digraph theory. 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 investigated 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, heuristics) in order to solve various optimization problems. We also investigate games on graphs as an algorithmic counterpart of some (di)graph theory studies to get more insight on problems and (di)graphs properties. One of the challenges we have to face in the design of algorithms is the increase in size of practical instances. It is difficult, if not impossible, to solve practical instances optimally using existing tools. Therefore, we have to find new ways to address problems using reduction and decomposition methods, characterization of polynomial instances (which are sometimes the practical ones), or design of algorithms with acceptable practical performances independently of the worst case time complexity.

- We study specific network optimization problems 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 chains of virtual functions (NFV), compact routing in large-scale networks, deployment and management of fleet of drones, design of reliable wireless networks, evolution of the routing in case of any kind 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, Huawei, Orange labs). We first contribute to the modeling of these problems; then we either use existing tools or develop new tools in Operation Research and (Di)Graph Theory to solve them.

- We also investigate optimization problems in other application fields (see Section 8.5) such as structural biology, transportation networks, economy, sociology, etc. For instance, we collaborate in Structural Biology with the Inria project-team ABS (Algorithms Biology Structure) from Sophia Antipolis. In the area of intelligent transport systems, we collaborate with the SMEs BeNomad and Instant-System on routing problems in multi-modal transportation systems. We also collaborate with GREDEG (research center in economics, law, and management) and the SKEMA business school on the analysis of the impact of competitive funding on the evolution of scientific networks.

  On the one side, these collaborations benefit to the considered domains via the dissemination of our tools. On the other side, they give rise to new problems of interest for our community, and help us to improve our knowledge and to test our algorithms on specific instances.

- Last but not least, the research done in COATI results in the production of software (WolrDynamics.jl, etc.), and in the contribution to large open-source softwares such as Sagemath.

Note also that besides our research activity, we are deeply involved in Terra Numerica and contribute to disseminating our domain towards a general audience.

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 (formerly ATHENA) on problems arising in computational neurosciences. In the area of transportation networks, we collaborate with SMEs Benomad and Instant-System on dynamic car-pooling combined with multi-modal transportation systems in the context of ANR project Multimod started in January 2018. 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

Joanna Moulierac is member of the I3S CO2 group since 2019. The objective of this working group is to evaluate the environmental impact of our research activities and to propose ways to make them evolve by 2030, in order to fulfill the Paris agreements (www.i3s.unice.fr/co2/).

6 Highlights of the year

6.1 Awards

- Ali Al-Zoobi and David Coudert received the best paper award of ICORES 2022 (11th International Conference on Operations Research and Enterprise Systems) for the paper entitled "*On Finding k Earliest Arrival Time Journeys in Public Transit Networks*" [64], a joint work with Arthur Finkelstein (Instant-System) and Jean-Charles Régin (I3S);

- Ilias Driouich received the best PhD student poster award of SophI.A Summit 2022 for the work entitled "*A Novel Model-Based Attribute Inference Attack in Federated Learning*";

- Foivos Fioravantes received the best PhD award in computer science of doctoral school ED STIC for his PhD entitled "*Distinguishing labellings of graphs*" [72], defended on September 26, 2022. He was co-supervised by Julien Bensmail and Nicolas Nisse;

- Hicham Lesfari, received the best PhD award of Foundation Université Côte d'Azur for his PhD entitled "*Machine learning for dynamic network resource allocation*", defended on October 7, 2022. He was supervised by Frédéric Giroire.

6.2 Promotions

- Joanna Moulierac has been promoted at the rank Associate Professor Hors-Classe in October 2022;
- Emanuele Natale received the Italian qualification as associate professor in Informatics from the National Ministry of Research and University (MIUR).

7 New software and platforms

7.1 New software

7.1.1 Graph Hyperbolicity

Keywords: Graph algorithmics, Algorithm engineering, Gromov hyperbolicity

Scientific Description: Hyperbolicity is a graph parameter related to how much a graph resembles a tree with respect to distances. Its computation is challenging as the main approaches consist in scanning all quadruples of the graph or using fast matrix multiplication as building block, both are not practical for large graphs. This software implements state-of-the-art algorithms and in particular new algorithms enabling to compute the hyperbolicity of graphs with unprecedented size (up to a million nodes) and speeds up the computation of previously attainable graphs.

Functional Description: Implementation in C++ of algorithms for computing the hyperbolicity of graphs.

URL: `https://gitlab.inria.fr/dcoudert/hyperbolicity`

Publications: hal-03431155, hal-03837023, hal-03438325

Contact: David Coudert

Participants: David Coudert, André Nusser, Laurent Viennot

7.1.2 k-shortest simple paths

Name: k-shortest simple paths

Keywords: Graph, Graph algorithmics

Functional Description: Implementation in C++ of algorithms for computing the k shortest simple paths from a source to a destination in a weighted directed graph.

Release Contributions: This version implements the standard algorithm proposed by Yen (Yen), Node Classification algorithm proposed by Feng (NC), the Sidetrack Based algorithm proposed by Kurz and Mutzel (SB), and variants of SB proposed by Al Zoobi, Coudert and Nisse to reduce running time (SB*) and memory usage (PSB). It also implements the PNC algorithm proposed by Al Zoobi, Coudert and Nisse to reduce the execution time of the NC algorithm.

URL: `https://gitlab.inria.fr/dcoudert/k-shortest-simple-paths`

Publications: hal-02865918, hal-03196830, hal-03438331

Contact: David Coudert

Participants: David Coudert, Nicolas Nisse, Ali Al Zoobi

7.1.3 SageMath

Name: SageMath

Keywords: Graph algorithmics, Graph, Combinatorics, Probability, Matroids, Geometry, Numerical optimization

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 and 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/`

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

Contact: David Coudert

Participants: David Coudert, Xavier Caruso

7.1.4 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.

News of the Year: The first version of WorldDynamics.jl has been released on September 2022. It includes all versions of the World models by Forrester and Meadows et al.

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

Contact: Emanuele Natale

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

Partner: Gran Sasso Science Institute

7.1.5 Idawi

Keywords: Java, Distributed computing, Web Services, Parallel computing, Component models, Software Components, P2P, Dynamic components, Internet of things, Distributed Applications

Functional Description: Idawi is a middleware for the development and experimentation of distributed applications for mobile multi-hop networks, such as the IoT, the Edge, Mobile Ad hoc Networks, etc. Its development was initially motivated by our need 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.

Idawi defines applications elements as components organized into a multi-hop overlay network on top of TCP/UDP and SSH, to be able to communicate 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 operations, which can be triggered remotely from anywhere in the component overlay.

The decentralized communication model of Idawi matches the very nature of mobile multi-hop networks. It defines that components communicate with each other via messages of bounded size. Messaging 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 of 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.

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

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

Contact: Luc Hogie

7.1.6 OnlineGraph

Keywords: Java, Distributed computing, Graph algorithmics

Functional Description: OnlineGraph is a decentralized mixed graph library. OnlineGraph is designed and developed as a specific application-level service of the Idawi middleware. It implements a decentralized application distributed over a multi-hop overlay network of components. In this application dedicated to the storage, edition and graphical rendering of graphs, graphs are partitioned over the set of components. The application imposes no allocation strategy: it is left to the application. A graph may be entirely allocated on one specific component, or a subset of the components forming the application, or all of them.

Any component in the application can expose graphs to the Web—not just its component-local part, but all the parts it has access to in the overlay networks. Graphs are then accessible to clients through a set of Web servers exposing services.

A component-local part of a partitioned graph consists of three correlated sets: the vertex set, the arc set, and the edge set. These sets can store the elements they contain in RAM or on disk, thereby enabling persistence. In these sets, graph elements are represented by a 64-bit numerical ID, and they can be associated to any data. This graph data structures can be used out of the distributed infrastructure, just any graph library.

OnlineGraph is developed within the COATI Research group at Inria Sophia Antipolis and I3S Computer Science Laboratory of Université Côte d'Azur](https://univ-cotedazur.eu/). Its development team is composed of:

Luc Hogie (project leader) Khadidiatou Dieye (Master's degree intern) Safouane Ouazri (Master's degree intern) Antonin Lacomme (Master's degree intern) Fedi Ghalloussi (Bachelor's degree intern)

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

Contact: Luc Hogie

8 New results

8.1 Network Design and Management

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 several 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 with the rises of several new paradigms like Software Defined Networks (SDN) and Network Function Virtualization (NVF), of new technologies like 5G, Elastic Optical Networks or LoRa, and of new usages like Internet of Things, 5G, High quality video streaming. Furthermore, the development of machine-learning based methods brings new tools that can help solving optimization problems. 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 efficiently route and place virtual resources in networks?
- How to use efficiently wireless networks?
- How to use machine-learning based methods for solving network optimization problems?

This very wide topic is considered by a lot of academic and industrial teams in the world. Our approach is to attack these problems with tools from operations research and discrete mathematics (some of them developed in our teams, see Sections 8.2 and 8.3). This approach is shared by a number of other teams worldwide, e.g. UFC and UNIFOR (Fortaleza, Brazil), Concordia Univ. (Montréal, Canada), Univ. Adolfo Ibañez (Santiago, Chile), Univ. Oran (Algeria), with which we have a direct collaboration.

8.1.1 Reconfiguring Network Slices at the Best Time With Deep Reinforcement Learning

Participants: Redha Alliche, Ramon Aparicio, Frédéric Giroire, Hicham Lesfari, Joanna Moulierac.

The emerging 5G induces a great diversity of use cases, a multiplication of the number of connections, an increase in throughput as well as stronger constraints in terms of quality of service such as low latency and isolation of requests. To support these new constraints, Network Function Virtualization (NFV) and Software Defined Network (SDN) technologies have been coupled to introduce the network slicing paradigm. Due to the high dynamicity of the demands, it is crucial to regularly reconfigure the network slices in order to maintain an efficient provisioning of the network. A major concern is to find the best frequency to carry out these reconfigurations, as there is a trade-off between a reduced network congestion and the additional costs induced by the reconfiguration.

In [59], we tackle the problem of deciding the best moment to reconfigure by taking into account this trade-off. By coupling Deep Reinforcement Learning for decision and a Column Generation algorithm to compute the reconfiguration, we propose Deep-REC and show that choosing the best time during the day to reconfigure allows to maximize the profit of the network operator while minimizing the use of network resources and the congestion of the network. Moreover, by selecting the best moment to reconfigure, our approach allows to decrease the number of needed reconfigurations compared to an algorithm doing periodic reconfigurations during the day.

8.1.2 Learning-based Packet Routing

Participants: Ramon Aparicio, Redha Alliche, Tiago da Silva Barros.

PRISMA: A Packet Routing Simulator for Multi-Agent Reinforcement Learning In [47], we present PRISMA (Packet Routing Simulator for Multi-Agent Reinforcement Learning), an open source simulation ns-3-based module. To the best of our knowledge, this is the first tool specifically conceived to develop and test Reinforcement Learning (RL) algorithms for the Distributed Packet Routing (DPR) problem. In this problem, where a communication node selects the outgoing port to forward a packet using local information, distance-vector routing protocol (e.g., RIP) are traditionally applied. However, when network status changes very dynamically, is uncertain, or is partially hidden (e.g., wireless ad-hoc networks or wired multi-domain networks), RL is an alternate solution to discover routing policies better fitted to these cases. Unfortunately, no RL tools have been developed to tackle the DPR problem, forcing the researchers to implement their own simplified RL simulation environments, complicating reproducibility and reducing realism. To overcome these issues, we present PRISMA, which offers to the community a standardized framework where: (i) communication process is realistically modelled (thanks to ns3); (ii) distributed nature is explicitly considered (nodes are implemented as separated threads); (iii) and, RL proposals can be easily developed (thanks to a modular code design and real-time training visualization interfaces) and fairly compared them. This work has been done in collaboration with Lucile Sassatelli from SIS team of I3S laboratory.

Impact Evaluation of Control Signalling onto Distributed Learning-based Packet Routing In recent years, several works have studied Multi-Agent Deep Reinforcement Learning for the Distributed Packet Routing problem, with promising results in various scenarios where network status changes dynamically, is uncertain, or is partially hidden (e.g., wireless ad hoc networks or wired multidomain networks). Unfortunately, these previous works focus on an ideal scenario where the impact of control signalling is neglected, and network simulation is tailored to simplistic assumptions. In [46], we present the first experimental investigation of control signalling mechanisms for distributed learning-based packet routing. We rely on PRISMA. We formulate two signalling mechanisms between agents (value sharing and model sharing). We investigate the net gains considering in-band signalling and show that routing policies close to those provided by an oracle with full knowledge of traffic and network topology can be discovered with a control overhead of 150% with respect to injected data packets, if neighboring agents share their Deep Neural Network models. We discuss the generality of our results to underline the importance of assessing net gains of Multi-Agent Deep Reinforcement Learning (MA-DRL)-based routing. This work has been done in collaboration with Lucile Sassatelli from SIS team of I3S laboratory.

8.1.3 Anomaly detection in traffic data

Participants: Frédéric Giroire, Hicham Lesfari.

With the continuous growing level of dynamicity, heterogeneity, and complexity of traffic data, anomaly detection remains one of the most critical tasks to ensure an efficient and flexible management of a network. Recently, driven by their empirical success in many domains, especially bioinformatics and computer vision, graph kernels have attracted increasing attention. Our work aims at investigating their discrimination power for detecting vulnerabilities and distilling traffic in the field of networking. In [63], we propose *Nadege*, a new graph-based learning framework which aims at preventing anomalies from disrupting the network while providing assistance for traffic monitoring. Specifically, we design a graph kernel tailored for network profiling by leveraging propagation schemes which regularly adapt to contextual patterns. Moreover, we provide provably efficient algorithms and consider both offline and online detection policies. Finally, we demonstrate the potential of kernel-based models by conducting extensive experiments on a wide variety of network environments. Under different usage scenarios, *Nadege* significantly outperforms all baseline approaches.

8.1.4 Modeling LoRa networks for the IoT

Participants: Christelle Caillouet.

LoRa is a low-power and long range radio communication technology designed for low-power Internet of Things devices. These devices are often deployed in remote areas where the end-to-end connectivity provided through one or more gateways may be limited. In collaboration with Martin Heusse and Andrzej Duda (Drakkar, LIG, Grenoble), we propose a model fitting the unslotted ALOHA protocol for channel access in a LoRaWAN cell [60, 69]. It combines the effects of collisions with channel fading, by which reception may get buried in noise. Unlike the existing models of LoRaWAN, our model takes into account the frame arrival timing: it distinguishes, on the one hand, the interference created by earlier transmissions with respect to the frame of interest, and on the other hand, the interference by the frames arriving later on. From the results of the model, we draw three observations regarding the improvement of Packet Delivery Ratio (PDR). First, it puts back under the spotlight the often overlooked fact that repeating frames is always beneficial when the desired PDR is above 60%, even though the extra packet transmissions create more collisions. Second, as soon as the node density becomes notable and collisions have a similar impact on losses as attenuation, adding a smaller spreading factor SF6 modulation into the cell list of transmission parameters allows increasing the coverage range. Third, the model shows that cell capacity sometimes grows with the distance to the gateway or with decreased node transmission power, a trend seldom observed in wireless networks.

8.1.5 Aerial networks for sensor coverage and energy harvesting

Participants: Christelle Caillouet, Igor Dias da Silva.

The use of autonomous unmanned aerial vehicles (UAVs) or drones has emerged to efficiently collect data from mobile sensors when there is no infrastructure available. The drones can form a flying ad-hoc network through which the sensors can send their data to a base station at any time. In [56], we present a mixed integer linear program to find the drones' optimal trajectories to form and maintain this network through time while minimizing their movements and energy consumption. Furthermore we analyze the trade-off between distance and energy, where increasing the drones' mobility can reduce their energy consumption, and derive a fair trade-off optimal solution to balance the two opposite objectives.

The problem of the lifetime of connected objects, in most use cases (Industrial Internet of Things (IIoT), disaster management, etc.) is an essential element of the proposed solutions. Radio frequency

(RF) harvesting of sensor batteries is an attractive solution, however, it does not scale up if it has to be done by human operators, and becomes impossible if the objects are located in unreachable places. An innovative solution consists of using fleets of drones to take care of this regular recharge. In collaboration with Yann Busnel (IMT Atlantique) [55], we focus on the self-organised deployment of a fleet of drones to solve this problem, taking into account the multiple constraints involved. We propose a two-step optimization framework based on an optimal orchestration solution to reduce the recharging time of a complete sensor system, by optimizing the number of drones, the overall flight time and their energy consumption. We illustrate the performance of our framework that ensures the drones avoid conflicts to guarantee a higher energy harvesting efficiency (establishment of optimal drone positions and planning of the global flight plan).

8.1.6 A middleware for the experimentation on IoT Mobile Networks

Participant: Luc Hogie *(*COATI, KAIROS*)*.

In the context of studies on decentralized algorithms for mobile dynamic networks, we investigated the state of the art of the experimentation tools. We discovered that existing solutions, either coming from labs or companies, do not match the requirements of experimentation as it is usually done by researchers. Indeed commercial products focus on reliability and interoperability at the expense of versatility, while lab tools most often serve as proof of concepts. The experimental study of algorithms requires the availability, in a single solution, of the following features: support for both synchronous and asynchronous communication, simulation/emulation of large systems, fast deployment, Web interoperability, and because less is more, full decentralization, just to name a few. Idawi was designed and implemented to the very purpose of providing the research community with a tool tailored to its needs. The resulting middleware, called Idawi is released via the MAVEN global distribution platform for Java software. MAVEN Central statistics indicate that Idawi binaries have been downloaded (for integration) 350 times in the year 2022. In addition to this, Idawi and its satellite tools are all Open Source. They are released under the Apache V2 license. For the sake of Open Science, their source code are fully available on GitHub. See [61, 62, 85]

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 approximation ones, 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 [95, 92], organization of the 10^{th} edition of GRASTA in May 2022...). 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 which satisfies some condition based on their initial input state.

8.2.1 Complexity of graph problems

Participants: Thomas Dissaux, Foivos Fioravantes, Nicolas Nisse.

Tree-decompositions with bags of bounded diameter A *path-decomposition* of a graph $G = (V, E)$ is a sequence of subsets of V, called *bags*, that satisfy some connectivity properties. The *length* of a path-decomposition of a graph G is the greatest distance between two vertices that belong to a same bag and the *pathlength*, denoted by $p\ell(G)$, of G is the smallest length of its path-decompositions. This parameter has been studied for its algorithmic applications for several classical metric problems like the minimum eccentricity shortest path problem, the line-distortion problem, *etc.* However, deciding if the pathlength of a graph G is at most 2 is NP-complete, and the best known approximation algorithm has a ratio 2 (there is no c-approximation with $c < \frac{3}{2}$ unless $P = NP$). In [82, 57], we focus on the study of the pathlength of simple sub-classes of planar graphs. We start by designing a linear-time algorithm that computes the pathlength of trees. Then, we show that the pathlength of cycles with n vertices is equal to $\lfloor \frac{n}{2} \rfloor$. Finally, our main result is a $(+1)$-approximation algorithm for the pathlength of outerplanar graphs. This algorithm is based on a characterization of almost optimal (of length at most $p\ell(G) + 1$) path-decompositions of outerplanar graphs.

Complexity of finding maximum locally irregular induced subgraphs If a graph G is such that no two adjacent vertices of G have the same degree, we say that G is *locally irregular*. In [68], we introduce and study the problem of identifying a largest induced subgraph of a given graph G that is locally irregular. Equivalently, given a graph G, find a subset S of $V(G)$ with minimum order, such that by deleting the vertices of S from G results in a locally irregular graph; we denote with I(G) the order of such a set S. We first examine some easy graph families, namely paths, cycles, trees, complete bipartite and complete graphs. However, we show that the decision version of the introduced problem is $\mathcal{NP}$-Complete, even for restricted families of graphs, such as subcubic planar bipartite, or cubic bipartite graphs. We then show that we can not even approximate an optimal solution within a ratio of $\mathcal{O}(n^{1-\frac{1}{k}})$, where $k \geq 1$ and n is the order the graph, unless $\mathcal{P}\mathcal{N}\mathcal{P}$, even when the input graph is bipartite.

Then, looking for more positive results, we turn our attention towards computing I(G) through the lens of parameterised complexity. In particular, we provide two algorithms that compute I(G), each one considering different parameters. The first one considers the size of the solution k and the maximum degree Δ of G with running time $(2\Delta)^k n^{\mathcal{O}(1)}$, while the second one considers the treewidth tw and Δ of G, and has running time $\Delta^{2tw} n^{\mathcal{O}(1)}$. Therefore, we show that the problem is FPT by both k and tw if the graph has bounded maximum degree Δ. Since these algorithms are not FPT for graphs with unbounded maximum degree (unless we consider $\Delta + k$ or $\Delta + tw$ as the parameter), it is natural to wonder if there exists an algorithm that does not include additional parameters (other than k or tw) in its dependency. We answer negatively, to this question, by showing that our algorithms are essentially optimal. In particular, we prove that there is no algorithm that computes I(G) with dependence $f(k)n^{o(k)}$ or $f(tw)n^{o(tw)}$, unless the ETH fails.

This is a joint work with with Nikolaos Melissinos (LAMSADE, Université Paris-Dauphine) and Theofilos Triomatis (School of Electrical Engineering, University of Liverpool).

8.2.2 Combinatorial games in graphs

Participants: Julien Bensmail, Jean-Claude Bermond, Michel Cosnard, Foivos Fioravantes, Frédéric Havet, Nicolas Nisse.

The largest connected subgraph game In [25], we introduce the *largest connected subgraph game* played on an undirected graph G. In each round, Alice first colours an uncoloured vertex of G red, and then, Bob colours an uncoloured vertex of G blue, with all vertices initially uncoloured. Once all the vertices are coloured, Alice (Bob, resp.) wins if there is a red (blue, resp.) connected subgraph whose order is greater than the order of any blue (red, resp.) connected subgraph. We first prove that, if Alice plays optimally, then Bob can never win, and define a large class of graphs (called *reflection graphs*) in which the game is a draw. We then show that determining the outcome of the game is PSPACE-complete, even in bipartite graphs of small diameter, and that recognising reflection graphs is GI-hard. We also prove that the game is a draw in paths if and only if the path is of even order or has at least 11 vertices, and that Alice wins in cycles if and only if the cycle is of odd length. Lastly, we give an algorithm to determine the outcome of the game in cographs in linear time. This is a collaboration with Fionn Mc Inerney (postdoc at CISPA Helmholtz Center for Information Security, Saarbrücken, Germany).

Then, in [48], we study the Maker-Breaker variant of this game, where Alice wins if there is a connected red component of order at least k, and otherwise, Bob wins. We want to compute $c_g(G)$, which is the maximum k such that Alice wins in G, regardless of Bob's strategy. Given a graph G and $k \in \mathbb{N}$, we prove that deciding whether $c_g(G) \geq k$ is PSPACE-complete, even if G is a bipartite, split, or planar graph. To better understand the Largest Connected Subgraph game, we then focus on *A-perfect* graphs, which are the graphs G for which $c_g(G) = \lceil |V(G)|/2 \rceil$, *i.e.*, those in which Alice can ensure that the red subgraph is connected. We give sufficient conditions, in terms of the minimum and maximum degrees or the number of edges, for a graph to be A-perfect. Also, we show that, for any $d \geq 4$, there are arbitrarily large A-perfect d-regular graphs, but no cubic graph with order at least 18 is A-perfect. Lastly, we show that $c_g(G)$ is computable in linear time when G is a P_4-sparse graph (a superclass of cographs). This is a collaboration with Fionn Mc Inerney (postdoc at CISPA Helmholtz Center for Information Security, Saarbrücken, Germany) and Nacim Oijid (Ph.D. student, LIRIS, Lyon).

The Vertex-Capturing Game Inspired by the board game *Kahuna*, we have introduced and studied in [33] a new 2-player scoring game played on graphs called the *vertex-capturing game*. The game is played on a graph by two players, Alice and Bob, who take turns colouring an uncoloured edge of the graph. Alice plays first and colours edges red, while Bob colours edges blue. The game ends once all the edges have been coloured. A player *captures* a vertex if more than half of its incident edges are coloured by that player, and the player that captures the most vertices wins.

Using classical arguments from the field, we have first proved general properties of this game. Namely, we have proved that there is no graph in which Bob can win (if Alice plays optimally), while Alice can never capture more than 2 more vertices than Bob (if Bob plays optimally). Through dedicated arguments, we have then investigated more specific properties of the game, and have focused on its outcome when played in particular graph classes. Specifically, we have determined the outcome of the game in paths, cycles, complete bipartite graphs, and Cartesian grids, and have given partial results for trees and complete graphs.

Graph grabbing games In [79, 50] we revisit the problem entitled SHARING A PIZZA stated by P. Winkler by considering a new puzzle called SHARING A PISSALADIERE. The game is played by two polite coatis Alice and Bob who share a pissaladière (a $p \times q$ grid) which is divided into rectangular slices. Alice starts in a corner and then the coatis alternate removing a remaining slice adjacent to at most two other slices. On some slices there are precious olives of Nice and the aim of each coati is to grab the maximum number of olives. We first study the particular case of $1 \times n$ grid (i.e. a path) where the game is a graph grabbing game known as SHARING A LINEAR PIZZA. In that case each player can take only an end vertex of the remaining path. These problems are particular cases of a new class of games called d-degenerate games played on a graph with non negative weights assigned to the vertices with the rule that coatis alternatively take a vertex of degree at most d.

Our main results are the following. We give optimal strategies for paths (linear pizzas) with no two adjacent weighty vertices. We also give a recurrence formula to compute the gains which depend only on the parity of n and of the respective parities of weighty vertices with a complexity in $\mathcal{O}(h^2)$ where h denotes the number of parity changes in the weighty vertices. When the weights are only $\{0,1\}$ we reduce the computation of the average number of olives collected by each player to a word counting problem. We solve SHARING PISSALADIÈRE with $\{0,1\}$ weights, when there is one olive or 2 olives. In that case Alice (resp. Bob) grabs almost all the olives if the number of vertices of the grid $n = p \times q$ is odd (resp. even). We prove that for a $2 \times q$ grid with a fixed number k of olives Bob grabs at least $\left\lceil \frac{k-1}{3} \right\rceil$ olives and almost always grabs all the k olives.

8.2.3 Optimal stopping algorithms

Participants: Malgorzata Sulkowska.

The optimal stopping theory is the art of choosing a proper time to take a particular action in order to maximize gain or minimize cost. In the series of articles we undertake several optimal stopping problems and come up with some tools that help to estimate the winning probabilities.

In [42] together with Fabrício Siqueira Benevides (UFC, Ceará, Brazil) we obtain a surprising result about a certain family of optimal stopping problems defined on graphs. The vertices of a graph G are revealed one by one, in a random order, to a selector. He aims to stop this process at a time t that maximizes the expected number of connected components in the graph $\tilde{G}_t$, induced by the currently revealed vertices. The selector knows G in advance, but different versions of the game are considered depending on the information that he gets about $\tilde{G}_t$. We show that when G has N vertices and maximum degree of order $o(\sqrt{N})$, then the number of components of $\tilde{G}_t$ is concentrated around its mean, which implies that playing the optimal strategy the selector does not benefit much by receiving more information about $\tilde{G}_t$. Results of similar nature were previously obtained by M. Lasoń for the case where G is a k-tree (for constant k). We also consider the particular cases where G is a square, triangular or hexagonal lattice, showing that an optimal selector gains cN components and we compute c with an error less than 0.005 in each case.

Next, we turn to a particular problem defined classically for uniform random variables. A decision maker observes a sequence of n independent realizations from the uniform distribution on the unit interval. However, he does not observe the precise values of these realizations, but only their ranks relative to those that have appeared previously. The goal of the decision maker is to select the realization whose value is closest to $\frac{1}{2}$. A realization can only be selected at the moment of its appearance. In [44], in collaboration with Ewa Kubicka, Grzegorz Kubicki (University of Louisville, USA) and Małgorzata Kuchta (WUST, Wrocław, Poland), we derive a stopping rule which maximizes the probability of achieving this goal, together with the asymptotic probability of success.

In cooperation with Alexander Gnedin (QMUL, London, UK) and Patryk Kozieł (WUST, Wrocław, Poland) we investigate much more general, full-information, models in [43]. The full-information best choice problem asks one to find a strategy maximizing the probability of stopping at the minimum (or maximum) of a sequence $X_1, \cdots, X_n$ of i.i.d. random variables with continuous distribution. We approach more general problem, where independent X_j's may have different distributions, discrete or continuous. A central role in our study is played by the running minimum process, which we first employ to re-visit the classic problem and its limit Poisson counterpart. The approach is further applied to two explicitly solvable models: in the first the distribution of the jth variable is uniform on $\{j, \cdots, n\}$, and in the second it is uniform on $\{1, \cdots, n\}$.

Finally, we come up with some tools that may be helpful by estimating winning probabilities in optimal stopping problems defined for tree-like graphs or partially ordered sets (posets). When deriving the optimal stopping rule, one needs to compare the probability of success by stopping the process at the current moment with the probability of success if one decided to play further. Then one is often forced to derive the number of embeddings of a currently generated structure (e.g. graph or poset) in the whole underlying structure. More precisely, the number of embeddings of a partially ordered set S in a partially ordered set T is the number of subposets of T isomorphic to S. If both, S and T, have only one unique maximal element, we define good embeddings as those in which the maximal elements of S and T overlap. In [39] (together with Bernhard Gittenberger, Isabella Larcher, TU Wien, Austria; and Zbigniew Gołębiewski, WUST, Wrocław, Poland) we investigate the number of good and all embeddings of a rooted poset S in the family of all binary trees on n elements considering two cases: plane (when the order of descendants matters) and non-plane. Furthermore, we study the number of embeddings of a rooted poset S in the family of all planted plane trees of size n. We derive the asymptotic behaviour of good and all embeddings in all cases and we prove that the ratio of good embeddings to all is of the order $\Theta(1/\sqrt{n})$ in all cases, where we provide the exact constants. Furthermore, we show that this ratio is asymptotically non-decreasing with S. Finally, we comment on the case when S is disconnected.

8.2.4 Algorithms for social networks

Participants: Frédéric Giroire, Nicolas Nisse, Stéphane Pérennes, Malgorzata Sulkowska.

Modularity in graphs and hypergraphs Modularity is a well-established parameter measuring the presence of community structure in the network. It was introduced by Newman and Girvan in 2004. Nowadays it is widely used as a quality function for community detection algorithms. The popular heuristic clustering algorithms (e.g., Louvain algorithm or Leiden algorithm) find a partition using modularity-based approach.

In [45] (in collaboration with Michał Lasoń from the Polish Academy of Sciences, Poland) we prove that a class of graphs with an excluded minor and with the maximum degree sublinear in the number of edges is maximally modular, that is, for every $\varepsilon > 0$, the modularity of any graph in the class with sufficiently many edges is at least $1-\varepsilon$. This completes the classification of maximally modular classes among all commonly considered subclasses of nowhere dense graphs with maximum degree sublinear in the number of edges.

Preferential attachment hypergraph with high modularity Numerous works have been proposed to generate random graphs preserving the same properties as real-life large scale networks. However, many real networks are better represented by hypergraphs. Few models for generating random hypergraphs exist and also just a few models allow to both preserve a power-law degree distribution and a high modularity indicating the presence of communities. In [83], we present a dynamic preferential attachment hypergraph model which features partition into communities. We prove that its degree distribution follows a power-law and we give theoretical lower bounds for its modularity. We compare its characteristics with a real-life co-authorship network and show that our model achieves good performances. We believe that our hypergraph model will be an interesting tool that may be used in many research domains in order to reflect better real-life phenomena. This is a collaboration with Thibaud Trolliet (MillionRoads).

A Random Growth Model with any Real or Theoretical Degree Distribution The degree distributions of complex networks are usually considered to follow a power law distribution. However, it is not the case for a large number of them. We thus propose a new model able to build random growing networks with (almost) any wanted degree distribution [38]. The degree distribution can either be theoretical or extracted from a real-world network. The main idea is to invert the recurrence equation commonly used to compute the degree distribution in order to find a convenient attachment function for node connections-commonly chosen as linear. We compute this attachment function for some classical distributions, as the power-law, the broken power-law, and the geometric distributions. We also use the model on an undirected version of the Twitter network, for which the degree distribution has an unusual shape. We finally show that the divergence of chosen attachment functions is directly linked to the heavy-tailed property of the obtained degree distributions.

8.2.5 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.

Algorithms for the k shortest simple paths problem The k shortest simple path problem (kSSP) asks to compute a set of top-k shortest simple paths from a vertex s to a vertex t in a digraph. Yen (1971) proposed the first algorithm with the best known theoretical complexity of $O(kn(m+n\log n))$ for a digraph with n vertices and m arcs. Since then, the problem has been widely studied from an algorithm engineering perspective, and impressive improvements have been achieved. The most noticeable proposals are the node-classification (NC) algorithm (Feng, 2014) and the sidetracks-based (SB) algorithm (Kurz, Mutzel, 2016). The latest offers the best running time at the price of a significant working memory. Last year, we proposed a new algorithm, the postponed node classification (PNC) algorithm, that combines the best of NC (low memory consumption) and SB (fast computation) [91]. This year, in collaboration with Arthur Finkelstein (I3S and Instant-System) and Jean-Charles Régin (I3S), we have extended in [64] the Yen's and PNC algorithms to find the k earliest arrival time journeys in public transit networks. The proposed PNC-PT algorithm (PNC for public transit networks) is currently the fastest algorithm for solving this problem.

Gromov hyperbolicity Hyperbolicity is a graph parameter which indicates how much the shortest-path distance metric of a graph deviates from a tree metric. It is used in various fields such as networking, security, and bioinformatics for the classification of complex networks, the design of routing schemes, and the analysis of graph algorithms. Despite recent progress, computing the hyperbolicity of a graph remains challenging. Indeed, the best known algorithm has time complexity $O(n^{3.69})$, which is prohibitive for large graphs, and the most efficient algorithms in practice have space complexity $O(n^2)$. Thus, time as well as space are bottlenecks for computing the hyperbolicity.

In collaboration with André Nusser (MPII, Saarbrücken, Germany) and Laurent Viennot (GANG, Inria Paris), we designed a tool for enumerating all *far-apart pairs* of a graph by decreasing distances [36], a key component that was previously used to drastically reduce the computation time for hyperbolicity in practice. However, it required the computation of the distance matrix to sort all pairs of nodes by decreasing distance. We proposed a new data structure that avoids this memory bottleneck in practice and for the first time enables computing the hyperbolicity of several graphs with more than 100 000 nodes that were far out-of-reach using previous algorithms. As iterating over far-apart pairs in decreasing order without storing them explicitly is a very general tool, we believe that our approach might also be relevant to other problems.

We then proposed in [52, 51] a new approach that uses a hierarchy of distance-k dominating sets to reduce the search space. This technique, compared to the previous best practical algorithms, enables us to compute the hyperbolicity of graphs with unprecedented size (up to a million nodes) and speeds up the computation of previously attainable graphs by up to 3 orders of magnitude while reducing the memory consumption by up to more than a factor of 23.

The C++ code of all our algorithms is available at [90].

8.2.6 Distributed algorithms

Participants: Francesco d'Amore, Frédéric Giroire, Hicham Lesfari, Emanuele Natale, Stéphane Perennes.

Phase Transition of the 3-Majority Dynamics with Uniform Communication Noise Communication noise is a common feature in several real-world scenarios where systems of agents need to communicate in order to pursue some collective task. In particular, many biologically inspired systems that try to achieve agreements on some opinion must implement resilient dynamics that are not strongly affected by noisy communications. In [66], in collaboration with Isabella Ziccardi (Università degli Studi dell'Aquila), we study the popular 3-Majority dynamics, an opinion dynamics which has been proved to be an efficient protocol for the majority consensus problem, in which we introduce a simple feature of uniform communication noise, following [93]. We prove that in the fully connected communication network of n agents and in the binary opinion case, the process induced by the 3-Majority dynamics exhibits a phase transition. For a noise probability $p < 1/3$, the dynamics reaches in logarithmic time an almost-consensus metastable phase which lasts for a polynomial number of rounds with high probability. Furthermore, departing from previous analyses, we further characterize this phase by showing that there exists an attractive equilibrium value $s_{eq} \in [n]$ for the bias of the system, i.e. the difference between the majority community size and the minority one. Moreover, the agreement opinion turns out to be the initial majority one if the bias towards it is of magnitude $\Omega(\sqrt{n \log n})$ in the initial configuration. If, instead, $p > 1/3$, no form of consensus is possible, and any information regarding the initial majority opinion is lost in logarithmic time with high probability. Despite more communications per-round are allowed, the 3-Majority dynamics surprisingly turns out to be less resilient to noise than the Undecided-State dynamics [93], whose noise threshold value is $p = 1/2$.

Phase transition of a nonlinear opinion dynamics with noisy interactions. In several real *Multi-Agent Systems* (MAS), it has been observed that only weaker forms of *metastable consensus* are achieved, in which a large majority of agents agree on some opinion while other opinions continue to be supported by a (small) minority of agents. In [37], we take a step towards the investigation of metastable consensus for complex (non-linear) *opinion dynamics* by considering the popular Undecided dynamics in the binary setting, which is known to reach consensus exponentially faster than the Voter dynamics. We propose a simple form of uniform noise in which each message can change to another one with probability p and we prove that the persistence of a metastable consensus undergoes a phase transition for $p = \frac{1}{6}$. Interestingly, our results have explicit connections to a specific setting of a well-studied value-sensitive decision mechanism inspired by cross-inhibition in house-hunting honeybee swarms.

Opinion dynamics We study opinion dynamics in multi-agent networks where agents hold binary opinions and are influenced by their neighbors while being biased towards one of the two opinions, called the superior opinion. The dynamics is modeled by the following process: at each round, a randomly selected agent chooses the superior opinion with some probability α, and with probability $1-\alpha$ it conforms to the opinion manifested by the majority of its neighbors. In [70], we exhibit classes of network topologies for which we prove that the expected time for consensus on the superior opinion can be exponential. This answers an open conjecture in the literature. In contrast, we show that in all cubic graphs, convergence occurs after a polynomial number of rounds for every α. We rely on new structural graph properties by characterizing the opinion formation in terms of multiple domination, stable and decreasing structures in graphs, providing an interplay between bias, consensus and network structure. Finally, we provide both theoretical and experimental evidence for the existence of decreasing structures and relate it to the rich behavior observed on the expected convergence time of the opinion diffusion model.

Parallel Lévy walks In collaboration with George Giakkoupis (WIDE Team, IRISA, Rennes) and Andrea Clementi (Univ. of Rome 2 "Tor Vergata", Rome, Italy), we investigated in [89] a parallel version of the famous Lévy walk stochastic process, the most famous general model of animal movement. This year, we presented our work at the Highlights of Algorithms (HALG) flagship international conference [86].

8.3 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 are putting an effort on understanding better directed graphs and partitioning problems, and in particular colouring problems. We also try to better understand the many relations between orientations and colourings. We study various substructures and partitions 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.

8.3.1 Partitioning and labelling graphs and digraphs

Participants: Julien Bensmail, Foivos Fioravantes, Frédéric Havet, Nicolas Nisse.

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 accordingly 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.

We have obtained a number of results, related both to the 1-2-3 Conjecture and related problems. These results stand both as notable progress towards some open questions, and as new problems of independent interest.

- In collaboration with H. Hocquard, D. Lajou and É. Sopena (LaBRI, Université de Bordeaux), we have investigated, through several works, the multiplicative version of the 1-2-3 Conjecture. In that variant of the 1-2-3 Conjecture, adjacent vertices are required to be distinguished, through a labelling, by their products of incident labels. The main conjecture here, is due to Skowronek-Kaziów, who conjectured in 2012 that labels $1,2,3$ should suffice for (nearly) all graphs. The best result towards that question, proved back in 2012, was that labels $1,2,3,4$ suffice in general.

  In [29], we have gotten progress towards that Multiplicative 1-2-3 Conjecture, proving that the conjecture holds for 4-colourable graphs, and providing a result that is very close to what is actually conjectured. Later on, in [28, 65], building upon that earlier study, we have come up with a full proof of the Multiplicative 1-2-3 Conjecture. This stands as one of the most important results of the field, in the recent years.

  In [30], we have also initiated the study of a list version of the Multiplicative 1-2-3 Conjecture, which is a standard way to generalise colouring/labelling problems. In particular, we conjecture that any lists of three labels should permit to design labellings distinguishing adjacent vertices by products. Towards that presumption, we have provided several results and bounds as support.

- In [20, 24, 27], with H. Hocquard, F. Fioravantes and D. Lajou, we have established the computational hardness of finding "optimal" labellings fulfilling additional constraints (e.g. when edges must be labelled in a proper way, when all vertices must be distinguished, and when the distinction condition is with respect to the incident sums, multisets and sets of labels). In particular, in the context of the so-called *irregular strength* of graphs, we even got close to establishing the NP-hardness of determining its value, which is a problem that has been open for long.

- In a few more works, we have also investigated several side aspects of the 1-2-3 Conjecture, resulting in the study of related variants. Notably, interesting questions relate to the labels $1,2,3$, which are at the heart of the conjecture. One can indeed legitimately wonder about the importance of these precise label values, and whether a similar question would still make sense when considering other label values.

  For instance, in [34], with F. Mc Inerney (CISPA Helmholtz Center for Information Security, Saarbrücken, Germany) and K. Lyngsie (Technical University of Denmark), we have investigated the generalisation of existing results with labels $1,2$ to any pair of odd labels a,b. While our results show that some results adapt naturally, they also highlight that some subtle discrepancies sometimes exist.

Also, in [49, 78], with H. Hocquard and P.-M. Marcille (LaBRI, Université de Bordeaux), we have investigated the so-called Weak $(2,2)$-Conjecture, which, roughly put, stands as a weaker form of the 1-2-3 Conjecture where label 3 is replaced with a pair of two particular labels (through the notion of coloured labels). As a main contribution, we have proved the conjecture for new significant classes of graphs, defined in terms of forbidden induced structures (claw-free graphs and $2K_2$-free graphs).

In some other works, we have also introduced new variants of distinguishing labelling problems, and have provided a few results on them. For instance, in [31], with H. Hocquard and P.-M. Marcille, we have introduced a variant of the 1-2-3 Conjecture where the vertex sums are fetched within a larger radius r, and it is required that vertices at distance at most r from each other must be distinguished. This problem encapsulating the exact 1-2-3 Conjecture (when $r = 1$), we have mainly investigated how existing results from the field generalize to larger values of r. In [26], we have considered a version where the sum of assigned labels must be minimised. Last, in [77], we have introduced a new variant dedicated to oriented graphs, standing as a generalisation of the 1-2-3 Conjecture to oriented colourings.

Arbitrarily Partitionable Graphs In [75, 32, 19], with B. Li (Northwestern Polytechnical University, China), we have investigated several properties of arbitrarily partitionable graphs (AP graphs for short), which are those graphs that can be vertex-partitioned into arbitrarily many connected subgraphs with arbitrary order. While AP graphs form a superclass of Hamiltonian graphs, we proved results showing both the similarities and the discrepancies between AP graphs and Hamiltonian graphs. In particular, we proved that a few sufficient conditions for Hamiltonicity can be weakened to APness, while we proved some do not, sometimes in a strong sense. We also investigated AP graphs that are minimal w.r.t. the AP property, giving results on their order, their minimum degree, their maximum degree, and their clique number.

Colouring decorated graphs In [22, 21, 23, 76] with T. Das, S. Das, S. Nandi and S. Sen (from various institutes in India), N. Oijid and T. Pierron (LIRIS, Université de Lyon), and D. Lajou and É. Sopena (LaBRI, Université de Bordeaux), we have pursued the study of the usual chromatic theory of graphs to the realm of decorated graphs. Namely, we have considered the analogue of the chromatic number for pushable graphs (oriented graphs in which vertices can be pushed at will, i.e., have the direction of their incident arcs reversed) and signed graphs (2-edge-coloured graphs in which vertices can be switched at will, i.e., have the polarity of their incident edges interchanged). We have mainly focused of graphs with bounded maximum degree. Notably, we have managed to determine the exact value of the analogues of the chromatic number for pushable graphs and signed graphs with maximum degree 3. We have also conducted a study of various types of grids, summarising the state of research of the field to date, and raising new results and questions.

Finally, we also came up with attempts to generalise classical types of colourings to signed graphs and oriented graphs, such as complete colourings and total colourings. For each such attempt, we investigated how results for the undirected case adapt to our case (if they did), and proposed new directions and questions to motivate further research on the topic.

Nash equilibria and greedy colourings Panagopoulou and Spirakis (A game theoretic approach for efficient graph coloring. *Algorithms and Computation* pages 183–195, 2008) proposed a colouring algorithm based on a game on a graph G. Each vertex is a player with action set corresponding to the set of colours $\{1,\dots,|V(G)|\}$. A configuration $\mathbf{c}$ is the combination of the actions of each vertex. Given a configuration, a player's payoff is 0 if he selects the same colour as one of his neighbours, otherwise it is the number of vertices that selected the same colour. An elementary improvement occurs when a player unilaterally deviates to other colour and increases its payoff. A *pure Nash equilibrium* (PNE) is a configuration in which no vertex can do elementary improvements. It can be seen as a state of the game that is *sustainable*. Note that pure Nash equilibria are colourings of G, because a vertex having a neighbour with its colour may increases its payoff by choosing any unused colour.

In [40], we introduce and study Nash colourings, that correspond to pure Nash equilibria in Panagopoulou and Spirakis's game: a **Nash k-colouring** is a k-colouring $(S_1,\dots,S_k)$ such that for all $i \in [k]$, every vertex v in S_i has a neighbour in each S_j, $j \neq i$, such that $|S_j| \geq |S_i|$. The *Nash number* $\mathrm{Nn}(G)$ is the largest k such that G has a Nash k-colouring. It measures the worst-case behaviour of Panagopoulou and Spirakis's algorithm. We fisrt prove that a Nash colouring is a greedy colouring which is diminishing. Thus the Nash number is at most the diminishing Grundy number $\Gamma^{\downarrow}(G)$, which in turn is at most the Grundy number $\Gamma(G)$. We prove some properties of Nn and $\Gamma^{\downarrow}$. We mainly study the relations between them and other graph parameters such as the clique number ω, the chromatic number χ, the Grundy number Γ, and the maximum degree Δ. In particular we study the chain of inequalities $\omega(G) \leq \chi(G) \leq \mathrm{Nn}(G) \leq \Gamma^{\downarrow}(G) \leq \Gamma(G) \leq \Delta(G)+1$. We show each inequality $\gamma_1(G) \leq \gamma_2(G)$ of this chain is loose, that is that there is no function f such that $\gamma_2(G) \leq f(\gamma_1(G))$. We also prove the existence or non-existence of Reed's like inequality who proved proved that there exists $\epsilon > 0$ such that $\chi(G) \leq \epsilon\omega(G) + (1-\epsilon)(\Delta(G)+1)$.

We then study the Nash number and the diminishing Grundy number of trees and forests, and prove that $\Gamma(F) - 1 \leq \mathrm{Nn}(F) \leq \Gamma^{\downarrow}(F) \leq \Gamma(F)$.

Finally we study the complexity of related problems. We show that computing the Nash number or the diminishing Grundy number is NP-hard even when the input graph is bipartite or chordal. We also show that deciding whether a graph satisfies $\gamma_1(G) = \gamma_2(G)$ is NP-hard for every pair (γ_1,γ_2) with $\gamma_1 \in \{\mathrm{Nn},\Gamma^{\downarrow}\}$ and $\gamma_2 \in \{\omega,\chi,\Gamma,\Delta+1\}$.

Colouring digraphs In [16], with Pierre Aboulker (DI ENS Paris) and Kolja Knauer and Clément Rambaud (Aix Marseille Université), we give bounds on the dichromatic number $\vec{\chi}(\Sigma)$ of a surface Σ, which is the maximum dichromatic number of an oriented graph embeddable on Σ. We determine the asymptotic behaviour of $\vec{\chi}(\Sigma)$ by showing that there exist constants a_1 and a_2 such that, $a_1\frac{\sqrt{-c}}{\log(-c)} \leq \vec{\chi}(\Sigma) \leq a_2\frac{\sqrt{-c}}{\log(-c)}$ for every surface Σ with Euler characteristic $c \leq -2$. We then give more explicit bounds for some surfaces with high Euler characteristic. In particular, we show that the dichromatic numbers of the projective plane $\mathbb{N}_1$, the Klein bottle $\mathbb{N}_2$, the torus $\mathbb{S}_1$, and Dyck's surface $\mathbb{N}_3$ are all equal to 3, and that the dichromatic numbers of the 5-torus $\mathbb{S}_5$ and the 10-cross surface $\mathbb{N}_{10}$ are equal to 4. We also consider the complexity of deciding whether a given digraph or oriented graph embeddable on a fixed surface is k-dicolourable. In particular, we show that for any fixed surface, deciding whether a digraph embeddable on this surface is 2-dicolourable is NP-complete, and that deciding whether a planar oriented graph is 2-dicolourable is NP-complete unless all planar oriented graphs are 2-dicolourable (which was conjectured by Neumann-Lara).

8.3.2 Structural digraph theory

Participants: Julien Bensmail, Frédéric Havet, Nicolas Nisse.

One of our goals is to establish structural results on digraphs that can then be used to design efficient algorithms. In particular, we are looking in finding substructures with certain properties or ways to represent or approximate efficently the digraphs.

Low chromatic spanning sub(di)graphs with prescribed degree or connectivity properties A folklore result in Graph Theory, attributed to Erdös, is that every graph G has a spanning bipartite subgraph H such that the degree of every vertex in H is at least half of its degree in G. It is easy to show that a spanning bipartite subgraph with the maximum number of edges has the desired property. Finding such a graph is the MAX-CUT problem, which is well-known to be NP-complete, but finding a subgraph H satisfying the above property can easily be done. As observed by Lovász, all this can be easily generalized to k-partite subgraphs: every graph $G=(V,E)$ on n vertices contains a spanning k-partite graph H satisfying $d_H(v) \geq \lceil\frac{k-1}{k} d_G(v)\rceil$ for every $v \in V$. In particular, G has a spanning k-partite subgraph with at least $\lceil\frac{k-1}{k}|E|\rceil$ edges. In [17], we first generalize those results: we show that every graph G contains a spanning k-partite subgraph H with $\lambda(H) \geq \lceil\frac{k-1}{k}\lambda(G)\rceil$, where $\lambda(G)$ is the edge-connectivity of G. In particular, together with a well-known result due to Nash-Williams and Tutte, this implies that every

7-edge-connected graphs contains a spanning bipartite graph whose edge set decomposes into two edge-disjoint spanning trees. We show that this is best possible as it does not hold for infinitely many 6-edge-connected graphs.

For directed graphs, we showed few years ago that there is no k such that every k-arc-connected digraph has a spanning strong bipartite subdigraph. We prove that every strong digraph has a spanning strong 3-partite subdigraph and that every strong semicomplete digraph on at least 6 vertices contains a spanning strong bipartite subdigraph. We generalize this result to higher connectivities by proving that, for every positive integer k, every k-arc-connected digraph contains a spanning $(2k+1)$-partite subdigraph which is k-arc-connected and this is best possible.

A conjecture due to Kreutzer, Oum, Seymour, van der Zypen, and Wood (*Electr. J. Comb.*, 24(2):P2.25, 2017) implies that every digraph of minimum out-degree $2k-1$ contains a spanning 3-partite subdigraph with minimum out-degree at least k. We prove that the bound $2k-1$ would be best possible by providing an infinite class of digraphs with minimum out-degree $2k-2$ which do not contain any spanning 3-partite subdigraph in which all out-degrees are at least k. We also prove that every digraph of minimum semi-degree at least $3r$ contains a spanning 6-partite subdigraph in which every vertex has in- and out-degree at least r.

Spanning eulerian subdigraphs in semicomplete digraphs A digraph is **eulerian** if it is connected and every vertex has its in-degree equal to its out-degree. Having a spanning eulerian subdigraph is thus a weakening of having a hamiltonian cycle. In [18], we first characterize the pairs (D,a) of a semicomplete digraph D and an arc a such that D has a spanning eulerian subdigraph containing a. In particular, we show that if D is 2-arc-strong, then every arc is contained in a spanning eulerian subdigraph. We then characterize the pairs (D,a) of a semicomplete digraph D and an arc a such that D has a spanning eulerian subdigraph avoiding a. In particular, we prove that every 2-arc-strong semicomplete digraph has a spanning eulerian subdigraph avoiding any prescribed arc. We also prove the existence of a (minimum) function $f(k)$ such that every $f(k)$-arc-strong semicomplete digraph contains a spanning eulerian subdigraph avoiding any prescribed set of k arcs. We conjecture that $f(k)=k+1$ and establish this conjecture for $k\leq 3$ and when the k arcs that we delete form a forest of stars.

A digraph D is **eulerian-connected** if for any two distinct vertices x,y, the digraph D has a spanning (x,y)-trail. We prove that every 2-arc-strong semicomplete digraph is eulerian-connected.

All our results may be seen as arc analogues of well-known results on hamiltonian paths and cycles in semicomplete digraphs.

8.3.3 Metric dimension in oriented graphs

The metric dimension $md(G)$ of an undirected graph G is the cardinality of a smallest set of vertices that allows, through their distances to all vertices, to distinguish any two vertices of G. Many aspects of this notion have been investigated since its introduction in the 70's, including its generalization to digraphs.

In [35], we study, for particular graph families, the maximum metric dimension over all strongly-connected orientations, by exhibiting lower and upper bounds on this value. We first exhibit general bounds for graphs with bounded maximum degree. In particular, we prove that, in the case of subcubic n-node graphs, all strongly-connected orientations asymptotically have metric dimension at most $\frac{n}{2}$, and that there are such orientations having metric dimension $\frac{2n}{5}$. We then consider strongly-connected orientations of grids. For a torus with n rows and m columns, we show that the maximum value of the metric dimension of a strongly-connected Eulerian orientation is asymptotically $\frac{nm}{2}$ (the equality holding when n,m are even, which is best possible). For a grid with n rows and m columns, we prove that all strongly-connected orientations asymptotically have metric dimension at most $\frac{2nm}{3}$, and that there are such orientations having metric dimension $\frac{nm}{2}$.

8.4 Machine learning theory and algorithms

Participants: Francesco d'Amore, Arthur Carvalho da Cunha, Ilias Driouich, Frédéric Giroire, Hicham Lesfari, Emanuele Natale, Chuan Xu.

In the last years, COATI has started investigating machine-learning-based methods to enhance algorithms or solve optimization problems in networks (see e.g., Sections 8.1.2 and 8.1.3). 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.

Revisiting and generalizing the Random Subset Sum problem The average properties of the well-known *Subset Sum Problem* can be studied by the means of its randomised version, where we are given a target value z, random variables $X_1, ..., X_n$, and an error parameter $\epsilon > 0$, and we seek a subset of the Xi's whose sum approximates z up to error ϵ. In this setup, it has been shown that, under mild assumptions on the distribution of the random variables, a sample of size $O(\log \frac{1}{\epsilon})$ suffices to obtain, with high probability, approximations for all values in $[-1/2, 1/2]$. Recently, this result has been rediscovered outside the algorithms community, enabling meaningful progress in other fields. In [81], we investigate we present an alternative proof for this theorem, with a more direct approach and resourcing to more elementary tools. An immediate multidimensional generalisation of the problem is to regard the random variables as d-dimensional random vectors and seek to approximate any point $z \in [-1,1]^d$. In 1998, G. S. Lueker showed that, in the one-dimensional setting, $n = \mathcal{O}(\log \frac{1}{\epsilon})$ samples guarantee the approximation property with high probability. In [74], we prove that, in d dimensions, $n = \mathcal{O}(d^3 \log \frac{1}{\epsilon} \cdot (\log \frac{1}{\epsilon} + \log d))$ samples suffice for the approximation property to hold with high probability.

Proving the Strong Lottery Ticket Hypothesis for Convolutional Neural Networks. The lottery ticket hypothesis states that a randomly-initialized neural network contains a small subnetwork which, when trained in isolation, can compete with the performance of the original network. Recent theoretical works proved an even stronger version: every sufficiently overparameterized (dense) neural network contains a subnetwork that, even without training, achieves accuracy comparable to that of the trained large network. These works left as an open problem to extend the result to convolutional neural networks (CNNs). In [53] we provide such generalization by showing that, with high probability, it is possible to approximate any CNN by pruning a random CNN whose size is larger by a logarithmic factor.

Patent deposit FR2210217: "Accurate programmable resistances from few inaccurate resistors". The high energy demands of modern Artificial Intelligence not only imply huge costs to run it at scale, but also constrains its deployment on edge devices. While analog computing offers a way to run those algorithms with orders of magnitude more efficiency, most proposals for its actual implementation require very high precision components and would depend on non-standard manufacturing. We propose a new method that uses a few inaccurate components to build accurate and programmable resistors, allowing analog neuromorphic devices to be manufactured with standard processes. It leverages the possibility of approximating any target value by summing a subset of given random values.

Privacy in federated learning In federated learning, clients such as mobile devices or data silos (e.g. hospitals and banks) collaboratively improve a shared model, while maintaining their data locally. Multiple recent works show that client's private information can still be disclosed to an adversary who just eavesdrops the messages exchanged between the targeted client and the server. In [67], we propose a novel model-based attribute inference attack in federated learning which overcomes the limits of gradient-based ones. Furthermore, we provide an analytical lower-bound for the success of this attack. Empirical results using real world datasets confirm that our attribute inference attack works well for both regression and classification tasks. Moreover, we benchmark our novel attribute inference attack against the state-ofthe-art attacks in federated learning. Our attack results in higher reconstruction accuracy especially when the clients' datasets are heterogeneous (as it is common in federated learning). Most importantly, our model-based fashion of designing powerful and explainable attacks enables an effective quantification of the privacy risk in FL.

8.5 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 8.2.5.

8.5.1 Graph algorithms for (low and high) resolution models of large protein assemblies

Participants: Frédéric Havet.

A macromolecular assembly is composed of subunits (e.g. proteins or nucleic acids). We assume that the composition, in terms of individual subunits, of selected complexes of the assembly is known. Indeed, a given assembly can be chemically split into complexes by manipulating chemical conditions, and the composition of these complexes can then be inferred using native mass spectrometry.

We then get a data set that can be represented by a hypergaph: a node represents a subunit, and the hyperedges represent the different complexes. The problem is then to find a graph G with the same vertex set as H whose edges represent the contacts between subunits, and satisfying (i) some local properties for every complex (i.e. hyperedge), and (ii) some other global properties. In [41], the considered local constraints is that G |it F-overlays H, that is the subgraph induced by G on every hyper-edge of H must have F as a spanning subgraph (for some fixed given F). The global contrainst is that $\Delta(G)$, the maximum degree of G, is at most k. We consider the computational complexity of a decision problem and a maximisation problem. The decision problem, called $\Delta \le k)$-F-OVERLAY problem, consists in deciding whether there is a graph with maximum degree at most k that F-overlays a given hypergraph. It is a particular case of the maximisation problem MAX $\Delta \le k)$-F-OVERLAY, which takes a hypergraph H and an integer s as input, and consists in deciding whether there is a graph with maximum degree at most k that F-overlays at least s hyperedges of H. We give a complete polynomial/NP-complete dichotomy for the MAX $\Delta \le k)$-F-OVERLAY problems depending on the pairs (F, k), and establish the complexity of $\Delta \le k)$-F-OVERLAY for many pairs (F, k).

Once the contact graph is obtained by solving the abiove problem, it serves as input graph for a second problem, called the domino problem, that consists in determining the high resolution structure of a given assembly. A configuration of a node is so a conformation of the corresponding protein (that is a position of each of its atoms in $\mathbb{R}^3$) and is obtained by X-ray cristallography. The domino problem can be modelled as a conflict-colouring problem. We are given a contact graph $G = (V, E)$, a list $C(v)$ of possible colours (configurations) for every node $v \in V$ and a bipartite graph between colour sets $C(u)$ and $C(v)$ for every edge $uv \in E$ which repersent the incompatible conformations of the two subunits. Then CONFLICT COLOURING consists in deciding whether there exists a conflict colouring, that is a colouring in which $c(u)c(v)$ is not an edge of the bipartite graph. In [84], we first establish the complexity dichotomies (polynomial vs NP-complete) for Conflict colouring and its variants. We provide some experiments in which we build instances of Conflict colouring associated to Voronoi diagram in the plane, and we then analyse the existences of a solution related to parameters used in our experimental setup. The domino problem consists in computing a configuration for each node maximizing some objective functions. Again, see the bioinformatics context below.

8.5.2 Analysis of temporal brain networks

Participants: Emanuele Natale, Aurora Rossi.

In collaboration with Samuel Deslauriers-Gauthier (ATHENA), we investigated in [88] properties of temporal brain networks extracted from functional Magnetic Resonance Imaging data. In particular, we focus on the temporal small worldness and, in order to test certain hypotheses of the observed functional connectivity, we propose three temporal null models: the geometric euclidean model on a square and on a torus, and the hyperbolic geometric graph model. The latter became famous in the research community investigating real-world complex networks, since it is able to model both a high tailed degree distribution and small worldness. We compare these models to a dataset of 1050 subjects' empirical data, taken from the WU-Minn Human Connectome Project, across different thresholds. Our analysis shows that the hyperbolic model is more consistent in reproducing the small worldness property of real data, thus providing evidence in its favor as a null model.

8.5.3 Planning with Biological Neurons and Synapses

Participants: Francesco d'Amore, Emanuele Natale.

In collaboration with Daniel Mitropolsky and Christos Papadimitriou (Columbia University, New York) and Pierluigi Crescenzi (GSSI, L'Aquila), we revisit in [87, 54] the planning problem in the blocks world, and we implement a known heuristic for this task. The program is written in the Assembly Calculus, a recently proposed computational framework meant to model computation in the brain by bridging the gap between neural activity and cognitive function. Its elementary objects are assemblies of neurons (stable sets of neurons whose simultaneous firing signifies that the subject is thinking of an object, concept, word, etc.), its commands include project and merge, and its execution model is based on widely accepted tenets of neuroscience. A program in this framework essentially sets up a dynamical system of neurons and synapses that eventually, with high probability, accomplishes the task. The purpose of this work is to establish empirically that reasonably large programs in the Assembly Calculus can execute correctly and reliably; and that rather realistic — if idealized — higher cognitive functions, such as planning in the blocks world, can be implemented successfully by such programs.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Amadeus, 2022-2024

Participants: Ilias Driouich, Frédéric Giroire, Chuan Xu.

- Collaboration with Amadeus funded by ANR in the context of "plan de relance". It supports the PhD thesis of Ilias Driouich under the co-supervision of Frédéric Giroire and Chuan Xu.

10 Partnerships and cooperations

10.1 International initiatives

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

EfDyNet

Title: Efficient Dynamic Resource Allocation in Networks

Duration: 2019-2022

Coordinator: Brigitte Jaumard (bjaumard@cse.concordia.ca)

Partners:

- Concordia University Montréal (Canada)

Inria contact: Frédéric Giroire

Summary: Networks are evolving rapidly in two directions. On the one hand, new network technologies are developed for different layers, and in particular flexible optical technologies (enabling to allocate a fraction of the optical spectrum rather than a fixed wavelength), Software Defined Networks, and Network Function Virtualization. On the other hand, the traffic patterns evolve and become less predictable due to the increase of cloud and mobile traffic. In this context, there are new possibilities and needs for dynamic resource allocations. We will study this problem mainly in two directions: network reconfiguration and the allocation of virtualized resources. The associated team will build on an already fruitful collaboration between COATI and Concordia. The two teams address design and management optimization problems in networks (WDM, wireless, SDN) with complementary tools and expertise.

10.2 International research visitors

10.2.1 Visits of international scientists

Other international visits to the team

Pierluigi Crescenzi

Status: Professor

Institution of origin: Gran Sasso Science Institute (GSSI)

Country: Italy

Dates: September 1st - October 31

Context of the visit: World Dynamics project for developing the WorldDynamics.jl Julia library.

Mobility program/type of mobility: international visitor grant by I3S laboratory and UCA$^{\text{JEDI}}$ Academie 1 RISE.

Guillaume Ducoffe

Status: Assistant Professor

Institution of origin: I.C.I., University of Bucharest

Country: Roumania,

Dates: July, 2022.

Context of the visit: work on the leanness of graphs

Mobility program/type of mobility: international visitor grant by I3S laboratory

Fatemehsadat Tabatabaeimehr

Status PhD

Institution of origin: Universitat Politècnica de Catalunya

Country: Spain

Dates: January 1st - March 31, 2022

Context of the visit: The main focus of this visit was the application of machine learning techniques (particularly, Long Short-Term Memories neural networks) to online network operation. In this regard, she has carried out the next tasks: i) design and implementation of the training methods employing the LSTM, ii) realization of the validation tests of such methods, and iii) analyses and presentation of the results.

Mobility program/type of mobility: research stay

10.2.2 Visits to international teams

Research stays abroad

Emanuele Natale

Visited institution: University of Rome Tor Vergata

Country: Italy

Dates: May 1st - July 31st

Context of the visit: Collaboration with Andrea Clementi's research group in Distributed Computing and teaching of a course in the Bachelor's degree in Computer Science at the University of Rome Tor Vergata.

Mobility program/type of mobility: Invited professor grant from University of Rome Tor Vergata.

Nicolas Nisse

Visited institution: Universidade Federal do Ceara

Country: Fortaleza, Brazil.

Dates: November 1-28th;

Context of the visit: Collaboration with Julio Araujo and other members of the ParGO team.

Mobility program/type of mobility: Invited professor grant from CAPES.

10.3 National initiatives

DGA/Inria Brainside, 2019-2023

Participants: Francesco D'Amore, Arthur Carvalho Walraven Da Cunha, Emanuele Natale.

Program: DGA/Inria

Project acronym: Brainside

Project title: Algorithms for simplifying neural networks

Duration: October 2019 - March 2023

Coordinator: Emanuele Natale

Other partners:

- Inria Paris, EP GANG

Summary: The widespread use of neural networks on devices with computationally-low capabilities, demands for lightweight and energy-efficient networks. Despite such need, and despite the strategies employed to prevent overfitting by removing a substantial part of their edges, the question of how to reduce their size in terms of the number of neurons appears largely unexplored. The aim of the project is to investigate algorithmic procedures to reduce the size of neural networks, in order to improve the speed with which they can be evaluated and to shed light on how much information about the computational problem at hand can be encoded within neural networks of small size.

ANR-17-CE22-0016 MultiMod, 2018-2023

Participants: Ali Al Zoobi, David Coudert, Nicolas Nisse, Michel Syska.

Program: ANR

Project acronym: MultiMod

Project title: Scalable routing in Multi Modal transportation networks

Duration: January 2018 - June 2023

Coordinator: David Coudert

Other partners:

- Inria Paris, EP GANG
- team CeP, I3S laboratory
- SME Instant-System
- SME Benomad

Summary: The MultiMod project addresses key algorithmic challenges to enable the fast computation of personalized itineraries in large-scale multi-modal public transportation (PT) networks (bus, tram, metro, bicycle, etc.) combined with dynamic car-pooling. We will use real-time data to propose itineraries with close to real travel-time, and handle user-constraints to propose personalized itineraries. Our main challenge is to overcome the scalability of existing solutions in terms of query processing time and data-structures space requirements, while including unplanned transportation means (car-pooling), real-time data, and personalized user constraints. The combination of car-pooling and PT network will open-up areas with low PT coverage enable faster itineraries and so foster the adoption of car-pooling. We envision that the outcome of this project will dramatically enhanced the mobility and daily life of citizens in urban areas.

Web: project.inria.fr/multimod/

ANR-19-CE48-0013 Digraphs, 2020-2023

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

Program: ANR

Project acronym: Digraphs

Project title: Digraphs

Duration: January 2020 - December 2023

Coordinator: Frédéric Havet

Other partners:

- LIRMM, Montpellier
- LIP, Lyon

Summary: The objectives of the project is to make some advances on digraph theory in order to get a better understanding of important aspects of digraphs and to have more insight on 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 second 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, EP FUN), Christophe Biernacki (vice-head, Inria, EP 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) which 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: Ilias Driouich, Frédéric Giroire, Chuan Xu.

Project acronym: Fed-Malin

Project title: Federated machine Learning over the internet

Duration: 2022 - 2026

Coordinators: Aurélien Bellet (Inria, EP MAGNET), Giovanni Neglia (Inria, EP 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.

10.3.1 GDR Actions

GDR RSD, ongoing (since 2006) Members of COATI are involved in the working group RESCOM (*Réseaux de communications*) of GDR RSD, CNRS (gdr-rsd.fr/pole-rescom). In particular, David Coudert was co-chair of this working group since 2017 until July 2022, and Christelle Caillouet is co-chair of this working group 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 IM, ongoing (since 2006) Members of COATI are involved in the working group "Graphes" of GDR IM, CNRS. (gtgraphes.labri.fr/). In particular, Frédéric Havet is member of the steering committee.

GDR MADICS, ongoing (since 2017) Members of COATI are involved in the working group GRAMINEES (GRaph data Mining in Natural, Ecological and Environnemental Sciences) of GDR MADICS (Masses de Données, Informations et Connaissances en Sciences). (www.madics.fr/actions/actions-en-cours/graminees/).

11 Dissemination

11.1 Promoting scientific activities

11.1.1 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.

11.1.2 Scientific events: organisation

General chair, scientific chair

- Nicolas Nisse
  - GRASTA 2022, General Chair, 10th Workshop on GRAph Searching, Theory and Applications, Porquerolles, France, May 16-20th, 2022.

Member of the organizing committees

- David Coudert :
  - 1st UCA QuantAzur days, Nice, France, June 16-17, 2022. www-sop.inria.fr/coati/events/quantazur2022/

11.1.3 Scientific events: selection

Member of the conference program committees

- Ramon Aparicio :
  - ACM MMSys: International Conference on Multimedia Systems, Dublin, Ireland, June. 2022;
  - ACM MM: International Conference on Multimedia, Lisbon, Portugal, October. 2022;
  - IEEE Globecom: IEEE Global Communications Conference, Rio de Janeiro, Brazil, December, 2022.
- Christelle Caillouet :
  - Cores'22: 7èmes Rencontres Francophones sur la Conception de Protocoles, l'Évaluation de Performance et l'Expérimentation des Réseaux de Communication, Saint-Rémy-Lès-Chevreuse, May 30 - June 2, 2022;
  - IOTSEQ: International Workshop on IoT Security and Quality of Service, Oct 19-21, 2022;
  - IEEE VTC2022-Fall: Track Unmanned Aerial Vehicle Communications, Vehicular Networks, and Telematics, London/Beijing, Sep 26-29, 2022;
  - IEEE WiSARN 2022: The 15th International Workshop on Wireless Sensor, Robot and UAV Networks, in conjunction with IEEE ICDCS 2022, Bologna, July 10-13, 2022;
- David Coudert:
  - AlgoTel: 24es Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications, Saint-Rémy-Lès-Chevreuse, May 30 - June 2, 2022;
  - ATMOS: Symposium on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems, Potsdam, Germany, September 8-9, 2022;
  - IEEE ICC: IEEE International Conference on Communications, Seoul, South Korea, May 16-20, 2022;
  - IEEE Globecom: IEEE Global Communications Conference, Rio, Brazil, December 4-8, 2022;
  - INOC: International Network Optimization Conference, Aachen, Germany, June 7-10, 2022;
  - ONDM: 26th Conference on Optical Network Design and Management, Warsaw, Poland, May 16-19 2022;
  - ROADEF: 23es congrès annuel de la société Française de Recherche Opérationnelle et d'Aide à la Décision, co-chair of stream *Optimisation dans les réseaux de télécommunication intelligents*, Lyon, France, February 23-25, 2022;
  - SEA: 20th Symposium on Experimental Algorithms, Heidelberg, Germany, July 25-27, 2022.
- Frédéric Havet:
  - ICGT 2022: 11th International Colloquium on Graph Theory and combinatorics, Montpellier, France, July 4-8, 2022.
  - JGA 2022: 24ème Journées Graphes et Algorithmes, Paris, November 16-18, 2022.
- Joanna Moulierac:
  - Cores'22: 7es Rencontres Francophones sur la Conception de Protocoles, l'Évaluation de Performance et l'Expérimentation des Réseaux de Communication, Saint-Rémy-Lès-Chevreuse, May 30 - June 2, 2022;
  - IEEE HPSR 2022: 23rd International Conference on High Performance Switching and Routing, Taicang, Jiangsu, China (Virtual sessions), June 6–8 2022.
- Emanuele Natale:

  - AAAI'23: Thirty-Seventh AAAI Conference on Artificial Intelligence.

- Nicolas Nisse :
  - AlgoTel 2022, 24es Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications, vallée de Chevreuse, May 30th-June 3rd, 2022.
  - SEA 2022, 20th Symposium on Experimental Algorithms, Heidelberg, Germany, July 25-27, 2022.

- Chuan Xu:
  - FL-NeurIPS'22: International Workshop on Federated Learning: Recent Advances and New Challenges in Conjunction with NeurIPS 2022. New orleans, USA, 2nd December, 2022
  - IEEE MSN'22: The 18th International Conference on Mobility, Sensing and Networking, GuangZhou, China, 14-16th December, 2022

11.1.4 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);
  - Telecom (MDPI).

- Frédéric Havet
  - Discrete Mathematics and Theoretical Computer Science (DMTCS).

- Emanuele Natale
  - The WikiJournal of Science (Wikimedia Foundation).

- Nicolas Nisse :
  - Discrete Applied Mathematics (Elsevier).

11.1.5 Invited talks

- David Coudert :
  - *On the k-shortest simple paths problem: time and space trade-offs*. Keynote speaker at the working group session of axis CAGDO and GT GT2L, ROADEF'22, February 25, 2022.
  - *A brief introduction to Sagemath*, tutorial at the Python working group seminar of the LINCS, March 23, 2022.
- Francesco d'Amore
  - *Search via Parallel Lévy Walks on $\mathbb{Z}^2$*, invited talk at the Wide team, Inria Rennes, Rennes, France, May 2022;
  - *Dynamics for Multi-Agent System Coordination in Noisy and Stochastic Environments*, invited talk at University of Hamburg, online seminar, May 2022;
  - *Phase transition of the 3-Majority dynamics with Uniform Communication Noise*, invited talk at the Third Italian Meeting on Probability and Mathematical Statistics 2022, Bologna, Italy, June 2022;
  - *On the Multidimensional Random Subset Sum Problem*, invited talk at Aalto University, Department of Computer Science, Espoo, Finland, September 2022.
- Frédéric Havet
  - *Substructures in digraphs*, School on graph theory, Murol, France, June 7-10, 2022.
- Nicolas Nisse
  - *Tree and Path decompositions with small diameter bags in subclasses of planar graphs* . Seminar of the ParGO team, Universidade Federal do Ceara, Fortaleza, Brazil. November 18th, 2022.
  - *Minimum lethal sets in grids and tori under 3-neighbour bootstrap percolation*, Workshop on Mobile Agents and Computing, Pisa, Italy, September, 21th, 2022.
- Małgorzata Sulkowska
  - *Modularity of minor-free graphs*, TCS seminar at Jagiellonian University, November 30, 2022

11.1.6 Leadership within the scientific community

- Christelle Caillouet :
  - Co-chair of *Pôle RESCOM of GDR RSD of CNRS* since July 2022.
- David Coudert :
  - Co-chair of *Pôle RESCOM of GDR RSD of CNRS* from 2017 till June 2022.
- 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 IM of CNRS* since 2005;
  - President of the PhD prize committee ; Graphes "Charles Delorme".

11.1.7 Scientific expertise

- Ramon Aparicio:
  - Expert for ANR.
- Julien Bensmail
  - External reviewer for the SONATA-17 program by the National Science Center (NSC) of Poland.
- Jean-Claude Bermond :
  - Expert for DRTT-MESR Crédit impôt recherche (CIR et agréments).
- David Coudert :
  - Expert for ANR;
- Frédéric Havet :
  - Expert for FNRS (Belgium).
- Emanuele Natale :
  - Expert reviewer for ANR.
  - Member of the Expert Panel "ST6 – Computer science and informatics" of the National Science Centre, Poland (NCN).
- Nicolas Nisse :
  - Expert for European Science Foundation (ESF)
- Michel Syska :
  - Expert for DRTT-MESR Crédit impôt recherche (CIR et agréments).

11.1.8 Research administration

- Ramon Aparicio:
  - Principal investigator of ARTIC project (ARTificial Intelligence-based Cloud network control), 220 k€ over 42 months funded by ANR JCJC 2019, March 2020 - Sept. 2024;
  - Representative of the I3S laboratory at the steering committee of Institut Fédératif Quantique Azuréen (IF QuantAzur) at Université Côte d'Azur, since February 2022;
  - Elected member of Conseil de Laboratoire du Laboratoire d'Informatique, Signaux et Systèmes de Sophia Antipolis (I3S) since March 2022.
- Christelle Caillouet
  - Elected member of Conseil de Laboratoire I3S since 2017;
  - Member of selection committee PRAG 134 and 135, Université Côte d'Azur, 2022.
- 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;

  - Nominated member for Inria at the board of doctoral school STIC, September 2017 - August 2022;
  - Head of the “Comité de Suivi Doctoral” of Inria, December 2019 - August 2022;
  - Nominated member for Inria at the steering committee of Academy 1 RISE (Networks, Information, Digital Society) of UCA$^{\mathrm{JEDI}}$, February 2018 - August 2022;
  - Nominated member for Inria at the steering committee of EUR DS4H, February 2018 - August 2022;
  - Nominated member for Inria at the steering committee of Labex UCN@Sophia, February 2018 - August 2022;
  - Member of the “Bureau du comité des équipe-projets” of Inria research center Sophia Antipolis - Méditerranée since 2018;
  - Member of the steering committee of seminar Forum Numerica of Academy 1 RISE of UCA$^{\mathrm{JEDI}}$ since 2018;
  - Representative of Inria at the steering committee of Institut Fédératif Quantique Azuréen (QuantAzur) at Université Côte d’Azur, since February 2022.

- 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
  - Head of COMRED team of I3S laboratory, till March 2022;
  - Coordinator of ANR project Digraphs.
  - President of selection committee PR 854, Université Côte d’Azur, 2022;
  - Co-head of Terra Numerica.

- Joanna Moulierac:
  - Member of selection committee MCF27 0105, Université Côte d’Azur, 2022;
  - Member of the CA of SPECIF-CAMPUS (Société Professionnelle des Enseignants et Chercheurs en Informatique de France);
  - Member of the I3S CO2 group since 2019 (www.i3s.unice.fr/co2/).

- Emanuele Natale:
  - External member of University of Rome Tor Vergata’s PhD School in Data Science (Italy).

- Nicolas Nisse :
  - Elected member for the "Comité de centre", Inria Sophia Antipolis - Méditerranée, since 2017;
  - 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 CoSP Terra Numerica, since 2020.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching Responsibilities

- Julien Bensmail :
  - Head of the Licence Professionnelle “Managements des Processus Logistiques” (MPL) of Université Côte d’Azur, since September 2019.
- Christelle Caillouet :
  - Member of the “Conseil de Département Informatique” of IUT Nice Côte d’Azur (since September 2022).
- 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 :
  - “Directrice d’études” for the 1st-year students of “Département Informatique” of IUT Nice Côte d’Azur (Sep. 2017 - March 2022);
  - 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);
  - Co 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 - défi du numérique", Université Côte d’Azur, Rectorat et Région PACA.

11.2.2 Teaching

Members of COATI have taught for more that 1400 hours (ETD) this year:

- DUT: Julien Bensmail, *Recherche opérationnelle*, 90h ETD, Level L2, Département QLIO of IUT, Université Côte d’Azur, France;
- DUT: Julien Bensmail, *Algorithmique et programmation avancées*, 64h ETD, Level L2, Département QLIO of IUT, Université Côte d’Azur, France;
- DUT: Francesco d’Amore, *Exploitation d’une base de données avancée*, 56h ETD, Level L1, Département Informatique of IUT Nice Côte d’Azur, UCA, France.
- DUT: Thomas Dissaux, *Communication et fonctionnement bas niveau*, 20h ETD, Level L1, Département Informatique of IUT, Université Côte d’Azur, France;
- DUT: Thomas Dissaux, *Introduction aux services réseaux*, 14h ETD, Level L1, Département Informatique of IUT, Université Côte d’Azur, France;
- DUT: Thomas Dissaux, *Initiation au développement*, 64h ETD, Level L1, Département Informatique of IUT, Université Côte d’Azur, France;

- DUT: Foivos Fioravantes, *Introduction aux bases de données*, 44h ETD, Level L1, Département Informatique of IUT, Université Côte d'Azur, France;
- DUT: Foivos Fioravantes, *Théorie des graphes*, 20h ETD, Level L1, Département Informatique of IUT, Université Côte d'Azur, France;
- DUT: Luc Hogie, *Distributed programming*, 24h ETD, Level L2, IUT, Université Côte d'Azur, France;
- DUT: Luc Hogie, *System programming*, 24h ETD, Level L2, IUT, Université Côte d'Azur, France;
- DUT: Hicham Lesfari, *Réseaux d'opérateurs et réseaux d'accès*, 48h ETD, Level L2, IUT, Université Côte d'Azur, France;
- DUT: Michel Syska, *Data Structures and Algorithms*, 44h ETD, Level L2, IUT, Université Côte d'Azur, France;
- DUT: Michel Syska, *Introduction to Artificial Intelligence*, 48h ETD, Level L2, IUT, Université Côte d'Azur, France;
- DUT: Michel Syska, *Algorithmics*, 30h ETD, Level L2, IUT, Université Côte d'Azur, France;
- DUT: Michel Syska, *Distributed programming*, 84h ETD, Level L2, IUT, Université Côte d'Azur, France;
- BUT: Joanna Moulierac, *Introduction aux Réseaux*, 56h ETD, Level L1, IUT, Université Côte d'Azur, France;
- BUT: Joanna Moulierac, *Réseaux avancés*, 30h ETD, Level L2, IUT, Université Côte d'Azur, France;
- PeiP: Joanna Moulierac, *Programmation Objet*, 30h ETD, Level L1, Polytech, Université Côte d'Azur, France;
- LP: Julien Bensmail, *Sécurité des échanges de données inter-entreprises*, 30h ETD, Level LP, LP MPL of IUT, Université Côte d'Azur, France;
- LP: Joanna Moulierac, *Programmation C#*, 30h ETD, Level L3, IUT, Université Côte d'Azur, France;
- Licence: Redha Abderrahmane Alliche, *Systèmes et Réseaux*, 24h ETD, Level L3, Polytech Nice-Sophia, France;
- Licence: Ali Al Zoobi, *Programmation et structures en C*, 24h ETD, Level L2, Faculté des sciences, Université Côte D'Azur, France;
- Licence: Michel Syska, *Networks*, 31h ETD, Level L3, MIAGE - 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, *Heuristic search*, 25h ETD, Level L3, parcours IA Science & Technologie - Université Côte d'Azur, France;
- Licence: Luc Hogie, *Programmation et Conception Orientée Objet*, 24h ETD, Level L3, parcours IA Science & Technologie - Université Côte d'Azur, France;
- License: Chuan Xu, *Programmation fonctionnelle*, 36h ETD, Level L3, Université Côte d'Azur, France;
- License: Chuan Xu, *Python pour l'IA*, 30h ETD, Level L3, parcours IA Science & Technologie - Université Côte d'Azur, France;
- License: Emanuele Natale, *Elements of Computational Modeling in Julia*, 3 Italian CFU (20h), bachelor's degree in Computer Science, University of Rome Tor Vergata, Italy (natema.github.io/ECMJ-it-2022/);

- Master: Christelle Caillouet, *Introduction Algorithmic and Programming*, 30h ETD, MAM3, Polytech Nice Sophia Antipolis, France;
- Master: Alexandre Caminada, *Radio location systems*, 20h ETD, Master 2 (in english), Polytech Nice Sophia, 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, France;
- Master: David Coudert, *Algorithms for Telecoms*, 36h ETD, M2 Ubinet, Université 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*, 24h 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: Hicham Lesfari, *Data mining for networks*, 12h ETD, Master 2, International Track Ubinet, 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: Nicolas Nisse, *Advanced Graphs*, 36h ETD, M2 Informatique et Interaction, Université Côte d'Azur, France;
- PhD: Emanuele Natale, *Elements of Computational Modeling in Julia*, 8h, PhD in Computer Science, Gran Sasso Science Institute, Italy (natema.github.io/ECMJ-GSSI-2022/).

11.2.3 Supervision

PhD thesis

- PhD in progress: Aurora Rossi, *Algorithmic aspects and random network models for temporal brain networks*, since October 2022. Co-supervisors: David Coudert and Emanuele Natale;
- PhD in progress: Redha Abderrahmane Alliche, *Artificial Intelligence-based cloud network control*, since October 2020. Co-supervisors: Ramon Aparicio and Lucile Sassatelli;
- PhD in progress: Arthur Carvalho Walraven Da Cunha, *Algorithmic Principles for Artificial Neural Network Compression*, since October 2020. Supervisor: Emanuele Natale;
- PhD in progress: Thomas Dissaux, *Graph decompositions and treelength*, since October 2020. Supervisor: Nicolas Nisse;
- PhD in progress: Igor Dias da Silva, *Optimization of UAVs deployment and coordination for exploration and monitoring applications*, since October 2020. Co-supervisors: Christelle Caillouet and David Coudert;
- PhD in progress: Lucas Picassari-Arrieta , *Digraph colourings*, since October 2021. Supervisor: Frédéric Havet;

- PhD in progress: Ilias Driouich, *Privacy-preserving algorithms for cross-device federated learning*. Co-supervisors: Frédéric Giroire and Chuan Xu. CIFRE grant with Amadeus;
- 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 and Frederic Giroire;
- PhD: Francesco d'Amore, *On the Collective Behaviors of Bio-Inspired Distributed Systems* [71], October 17, 2022. Co-supervisors: Emanuele Natale and Nicolas Nisse;
- PhD: Foivos Fioravantes, *Distinguishing labellings of graphs* [72], September 26, 2022. Co-supervisors: Julien Bensmail and Nicolas Nisse;
- PhD: Hicham Lesfari, *Foundations of Networks towards AI*, October 7, 2022. Supervisor: Frédéric Giroire;
- PhD: Zhejiayu Ma, *Learning-based optimization of hybrid CDN/V2V live streaming systems*, December 20, 2022. Co-Supervisors: Guillaume Urvoy-Keller, Frédéric Giroire, Soufiane Rouiba (Easybroadcast, Nantes). CIFRE grant with Easybroadcast.

Internships

- Licence: Yannis Belkhiter, *Development of a game in Mobile Apps for the scientific communication*, Mines d'Alès, France, July-August 2022. Supervisor: Nicolas Nisse.
- Licence: Samuel Coulomb, *Fast algorithm for the Leanness of Graphs*, ENS Ulm, France, from June 7 till July 29, 2022. Supervisor: David Coudert.
- Licence: Baptiste Thierry, *Graph grabbing games* , UCA, France, from May 16 till July 28, 2022. Supervisor: Jean-Claude Bermond and Michel Cosnard and Frédéric Havet.
- Google Summer of Code: Enjeck Mbeh Cleopatra, *implementation of preprocessing methods for edge connectivity in digraphs in Sagemath*, BSc University of Bamenda, Cameroon, from May till November 2022. Mentor: David Coudert.
- Google Summer of Code: Georgia Channing, *implementation of Gabow's arborescence packing algorithm in Sagemath*, MSc University of Tennessee, Knoxville, USA, from May till September 2022. Mentor: David Coudert.
- Master : Javier Fernandez Cordova and Johannes Rüscher , *Energy efficiency of slice placement in 5G networks*, project of MSc IT of IMT Atlantique, from March till May 2022. Supervisors: Christelle Caillouet and Géraldine Texier (IMT Atlantique).
- Master 1: Margaux Schmied, *on the computation of shortest smooth path with uniformly bounded stretch*, Master 1 Computer Science, Université Côte d'Azur, from July till August 2022. Supervisor: David Coudert.
- Master 1: Pierre Kouyoumdjian, *Modularity and* 2*-community structure in graphs*, Master 1 Computer Science, Université Côte d'Azur, from July till August 2022. Supervisor: Nicolas Nisse.
- Master 1: Antoine Cousson, *Quantum Entanglement Management*, Master 1 informatique, Université Côte d'Azur, France, from June 2022 until July 2022. Supervisor: Ramon Aparicio.
- Master 2: Marco Dinuzzi (TER), *Calculating the Carbon Footprint of Streaming Media*, M2 IFI, international track Ubinet, Université Côte d'Azur, France, from October 2022 until February 2023. Supervisors: Joanna Moulierac and Guillaume Urvoy-Keller.
- Master 2 (TER+internship): Maria Darido, *Data acquisition and collection in harsh environment*, M2 IFI parcours Ubinet, Université Côte d'Azur, France, from October 2021 until August 2022. Supervisors: Christelle Caillouet and David Coudert.

- Master 2 (TER+internship): Leonardo Serilli, *Evolution over time of the structure of social graphs: Clustering*, M2 IFI parcours Ubinet, Université Côte d'Azur, France, from October 2021 until August 2022. Supervisors: Frédéric Giroire and Nicolas Nisse and Malgorzata Sulkovska.
- Master 2 (TER+internship): El Hassam Chokraallah, *Using Semantic Graph clustering to explore study and career paths with the goal to Help student and professional counseling*, M2 IFI parcours Ubinet, Université Côte d'Azur, France, from October 2021 until August 2022. Supervisors: Frédéric Giroire and Nicolas Nisse and Malgorzata Sulkovska.
- Master 2: Tiago da Silva Barros, *Network simulator for reinforcement learning*, Master 2 Ingénierie informatique, international track Ubinet, Université Côte d'Azur, France, from March 2022 until August 2022. Supervisor: Ramon Aparicio.
- Master 2 : Aurora Rossi, *The Hyperbolic Model and the Temporal Small Worldness of Brain Dynamics*, Master 2 in Mathematics, University of Verona, Italy, from February 2022 until August 2022. Supervisor: Emanuele Natale.
- Predoc : Edward Amadeus Reinald, *Reconfiguration of directed colourings*, 4th year of ENS Lyon, from February 2022 until May 2022. Supervisor: Frédéric Havet.
- Predoc : Clément Rambaud, *Inversions in digraphs*, 4th year of ENS Paris, from September 2022 until March 2023. Supervisor: Frédéric Havet.

11.2.4 Juries

- Ramon Aparicio:
  - Referee of PhD thesis of Fatemehsadat Tabatabaeimehr, Université Polytechnique de Catalogne, Barcelone, Espagne, June 2, 2022;
  - Referee of PhD thesis of Sima Barzegar, Université Polytechnique de Catalogne, Barcelone, Espagne, June 2, 2022.
- Julien Bensmail
  - Reviewer of the Ph.D. thesis of Fabien Jacques on *Homomorphismes de graphes signés et complexité de quelques problèmes d'homomorphismes*, Université de Montpellier, France, July 11, 2022.
- Christelle Caillouet :
  - Member of the PhD committee of Mohamed Hamnache on *Performances et Gestion de l'itinérance dans les réseaux LoRaWAN*, Toulouse INP, France, Nov 25, 2022;
  - Member of the PhD committee of Jean-Philippe Abegg on *Sécurité et efficacité des technologies Blockchain appliquées à l'internet des objets*, Université de Strasbourg, France, Oct 21, 2022;
  - Member of the PhD committee of Amal Boubaker on *Performances des protocoles de transport dans les constellations de satellites*, Toulouse INP, France, May 4, 2022.
- David Coudert :
  - Member (and president) of the PhD committee of Arthur Finkelstein on *Recherche de plus court chemin multimodal de point à point dépendant du temps*, Université Côte d'Azur, France, September 22, 2022.
- Frédéric Havet :
  - Member (and president) of PhD committe of Julien Devreton, Université Côte d'Azur, France, Avril 6, 2022.
- Nicolas Nisse :
  - Referee and member of PhD committe of Tobias Castanet, Université de Bordeaux, September 12, 2022.

11.3 Popularization

Coati is deeply involved in Terra Numerica. Its members are very active in content creation, dissemination to the public, training of teaching or facilitating staff, and project governance.

Frédéric Havet and Nicolas Nisse are also involved in the ANR project ASMODEE (Analyse et conception de situations de médiation en informatique débranchée) headed by LIRIS laboratory.

11.3.1 Internal or external Inria responsibilities

Frédéric Havet is co-head of Terra Numerica and one of the responsible of the “Comité Scientifique, Pédagogique et Technique” ; Nicolas Nisse is a member of this comité ; 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.

11.3.2 Articles and contents

COATI members have participated in the development of numerous mediation devices for Terra Numerica. We only list below the most important ones.

- Galejade: Frédéric Havet, Joanna Moulierac, and Nicolas Misse importantly participate in the Galejade project whose aim is to provide funny and interactive activities to approach mathematics and computer science by getting out of pencil paper and computers. A first handbook has been made available on Hal [94]. Since its release, it has been downloaded several thousands of times.
- Two-Player games in graphs: Nicolas Nisse co-supervised with Dorian Mazauric (ABS) Yannis Belkhiter (intern, first year engineering school, Mines d’Ales), who designed a popularization software about the surveillance game, related to prefetching problems.
- Green Networks: Frédéric Giroire and Joanna Moulierac created of a scientific popularization activity on the energy efficiency in networks on a 2m50 by 3m20 model representing a city. This activity takes place in the main hall of Terra Numerica, Valbonne and is largely appreciated by the public.
- Walk of ants: Frédéric Havet and Luc Hogie created an activity to explain how a simple decentralized algorithm allows ants to find shortest paths. They supervised the internships of Thimotée Juillet (2nd year IUT) to develop a numerical application and the internships of Matthis Kuhl, Quentin Scordo and Lucas Lyon (DS4H) to program robots behaving like ants.
- Hanoi towers: Frédéric Havet co-supervised with Dorian Mazauric (ABS) Antoine Agré (intern, second year engineering school) and Mael Rivière, who designed a popularization software about Hanoi towers.

Frédéric Havet and Luc Hogie co-supervised with Dorian Mazauric (ABS team) five TER of EUR DS4H to develop various popularization softwares (Lucas Lyon, Quentin Scordo, David Prigodin, Milena Kostov, and Chahan Movsessian).

Nicolas Nisse participated to the WECAM (WeekEnd Création d’Activité de Médiation) Türing, Lyon, February 5-6th, 2022.

11.3.3 Education

Members of COATI participated to the receptions of 3ème trainees:

- 12 trainees, January 31–February 4, 2022 (T. Dissaux, F. Havet, J. Moulierac, N. Nisse, L. Picasarri-Arrieta).
- 15 trainees, December 12–16, 2022 (F. Havet, N. Nisse)

Members of COATI participated to the training of teachers:

- Training for 25 secondary school teachers in Toulon, March 2022. *Algorithms*, by F. Havet and N. Nisse.
- Training for 40 primary school teachers in Rians, May 2022. *Galejade method*, by F. Havet and N. Nisse.
- Training for 25 secondary and high school teachers in Valbonne, March 2022. *Tilings*, by F. Havet.
- Training for 25 primary school teachers in Valbonne, October 2022. *Galejade method*, by F. Havet.

Many members of Coati (J.-C. Bermond, M. Cosnard, T. Dissaux, F. Havet, H. Lesfari, J. Moulierac, L. Picasarri-Arrieta) ran numerous popularization activities in front of schoolgirls and schoolboys, either at TerraNumerica@Sophia, at MIA (Maison de l'Intelligence Artificielle), or in their schools. Some were part of some national programmes such as "Chiche !", "Cordées de la réussite", or "Maths en Jeans".

11.3.4 Interventions

Many members of Coati (T. Dissaux, F. Giroire, F. Havet, H. Lesfari, J. Moulierac, L. Picasarri-Arrieta, S. Pérennes, C. Rambaud, M. Syska) participated some general audience science fairs like the inauguration of TerraNumerica@Sophia on June 11th 2022, and Fête de la science in October 2022 (we were present on the "Village des Sciences" in Antibes-Juan-les-Pins, Valbonne, Villeneuve-Loubet, Vinon-sur Verdon).

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

12 Scientific production

12.1 Major publications

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12.2 Publications of the year

International journals

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