RESEARCH CENTRE

**Nancy - Grand Est**

**IN PARTNERSHIP WITH:**

**Université de Lorraine, CNRS**

# 2021 ACTIVITY REPORT

# Project-Team PASTA

## Space-time random processes and applications

**IN COLLABORATION WITH: Institut Elie Cartan de Lorraine (IECL)**

**DOMAIN**

**Applied Mathematics, Computation and Simulation**

**THEME**

**Stochastic approaches**

# Contents

# Project-Team PASTA

*Creation of the Project-Team: 2020 December 01*

## Keywords

**Computer sciences and digital sciences**

A6.1.2. – Stochastic Modeling

A6.2.2. – Numerical probability

A6.2.3. – Probabilistic methods

A6.2.4. – Statistical methods

A6.3.3. – Data processing

**Other research topics and application domains**

B3.3.1. – Earth and subsoil

B3.4.1. – Natural risks

B9.6.3. – Economy, Finance

B9.11. – Risk management

B9.11.1. – Environmental risks

B9.11.2. – Financial risks

# 1 Team members, visitors, external collaborators

## Research Scientists

- Madalina Deaconu [Team leader, Inria, Researcher, HDR]
- Antoine Lejay [Inria, Senior Researcher, HDR]

## Faculty Members

- Sara Mazzonetto [Univ de Lorraine, Associate Professor, from Dec 2021]
- Pascal Moyal [Univ de Lorraine, Professor, HDR]
- Radu Stoica [Univ de Lorraine, Professor, HDR]

## PhD Students

- Alexis Anagnostakis [Univ de Lorraine]
- Jocelyn Begeot [Univ de Lorraine]
- Nicolas Dante [Univ de Lorraine]
- Laurent Lesage [Univ du Luxembourg]
- Zhanhao Liu [Saint-Gobain Research Paris, until Jun 2021]
- Thomas Masanet [École normale supérieure Paris-Saclay]
- Christophe Reype [Univ de Lorraine]

## Technical Staff

- Katarzyna Adamczyk Chauvat [Institut national de recherche pour l'agriculture, l'alimentation et l'environnement, Engineer, from Oct 2021]

## Interns and Apprentices

- Rémy Banel [Inria, from Apr 2021 until Sep 2021]
- Léo Gaillard [Inria, from Apr 2021 until Sep 2021]
- Hajar Hanafi [Univ de Lorraine, from Jul 2021 until Aug 2021]
- Amine Landa [Univ de Lorraine, from Jun 2021 until Oct 2021]
- Theodor Lemerle [Univ de Lorraine, from Apr 2021 until Sep 2021]
- Pierre Alexandre Simon [Univ de Lorraine, from Feb 2021 until Jul 2021]
- Nassim Tanaje [Univ de Lorraine, from Jun 2021 until Oct 2021]

## Administrative Assistant

- Isabelle Blanchard [Inria]

## 2 Overall objectives

PASTA is a joint research team between Inria - Nancy Grand Est, CNRS and University of Lorraine, located at Institut Élie Cartan of Lorraine.

PASTA aims to construct and develop new methods and techniques by promoting and interweaving stochastic modeling and statistical tools to integrate, analyze and enhance real data.

The specificity and the identity of PASTA are:

- the embedding of spatio-temporal statistics and stochastic process analysis into models to tackle challenging complex problems that require new mathematical techniques, by combining the strengths of these two scientific domains.

- to deal with the increase of available data, the construction of suitable models which incorporate prior knowledge on their spatio-temporal structures. For this, we design and analyze simulation and inference techniques, and focus on the interpretation, the validation and the explanation of both the models and the algorithms, in close interaction with practitioners.

The leading direction of our research is to develop the topic of *data enriched* spatio-temporal stochastic models, through a mathematical perspective. Specifically, we jointly leverage major tools of probability and statistics: data analysis and the analytical study of stochastic processes. We aim at exploring the three different aspects, namely: shape, time and environment, of the same phenomenon. These mathematical methodologies will be intended for solving real-life problems through inter-disciplinary and industrial partnerships.

## 3 Research program

Our research program develops three interwoven axes:

- stochastic modeling,

- simulation algorithms,

- inference and data analysis.

In particular, we are interested in the evolution of stochastic dynamical systems evolving in intricate configuration spaces. These configuration spaces could be spatial positions, graphs, physical spaces with singularities, space of measures, space of chemical compounds, and so on.

While facing a new modeling question, we have to construct the appropriate class of models among what we call the *meta-models*. Meta-models and then models are selected according to the properties to be simulated or inferred as well as the objectives to be reached. Among other examples of such meta-models which we regularly use, let us mention *diffusion processes*, *Gibbs measures*, *multivariate time series* and *random graphs*. On these topics, the team has an intensive research experience from different perspectives.

Finding the balance between usability, interpretability and realism is our first guide. This is the keystone in modeling, and the main difference with black-box approaches in machine learning. Our second guide is to study the related mathematical issues in modeling, simulation and inference. Models are sources of interesting open mathematical questions. We are eager to expand the “capacity” of the models by exploring their mathematical properties, providing simulation algorithms or proposing more efficient ones, as well as new inference procedures with statistical guarantees.

To study and apply the class of stochastic models we consider, we have to handle the following questions:

- *modeling*: identifying the quantities of interest, the nature of the randomness, the nature of their dynamical evolution and the useful variables. Finally, we have to specify the statistical properties of the stochastic process at stake: Markov or long-range dependency, time/space-stationarity or transience, integrability, and so on.

- *stochastic analysis*: providing rigorous tools to manipulate the model and evaluating its characteristics in steady state or in transient regime (hitting times of a given state, rare events, etc.).
- *simulation*: if the stochastic process is transient, or the equilibrium state is intractable, replicating the (possibly erratic in time and/or space) behavior of the system by efficient simulation algorithms, such as perfect simulation, adapted MCMC (Monte Carlo Markov Chain) algorithms or any other suitable numerical scheme. Rigorously proving the amenability of such algorithms for their use in statistical inference.
- *inference*: specifying tools to evaluate in a parametric or non-parametric setting in the appropriate context (frequentist or Bayesian), developing the suitable numerical methods (stochastic algorithms, MCMC) and getting bounds on the quality of the estimation.

# 4 Application domains

Our main application domains are: insurance, geophysics, geology, medicine, astronomy and finance.

We aim at providing new tools regarding the modeling, simulation and inference of spatio-temporal stochastic processes and other dynamical random systems living in large state-spaces. As such, there are many application domains which we consider.

In particular, we have partnerships with practitioners in: cosmology, geophysics, healthcare systems, insurance, and telecom networks.

We detail below our actions in the most representative application domains.

## 4.1 Geophysics

Geophysics is a domain which requires the application of a broad range of mathematical tools related to probability and statistics while more and more data are collected. There are several domains in which we develop our methodology in relation with practitioners in the field.

- Avalanches (snow or rock) present intricate dynamical properties, with a wide variety of behaviors that largely depend on their environments. To model such phenomena, we apply tools from fragmentation theory, stochastic calculus, partial differential equations and branching processes. Our approach is new and paves the way to considering and constructing rigorous mathematical models and simulation procedures able to reproduce and control the real phenomenon by introducing more and more issues in the models.
- Understanding the behavior of subsurface and surface fluids is a major challenge in geophysics. We deal with two main axes: (1) using tools for spatial Bayesian statistics which consists in detecting the sources of the various components of fluids from their hydrogeochemical data, and (2) developing the suitable methodological and numerical tools to simulate diffusion processes (pollutant, water...) moving in heterogenous media in the presence of interfaces.
- Earthquake forecasting is notoriously difficult. To grasp the statistical distribution of seismic hazards, we consider setting up tools to detect seismic faults using marked point processes. Such a project presents challenging aspects concerning both the inference and the simulation of the processes.

On such topics, we hold long standing interdisciplinary collaborations with INRAE Grenoble, the RING Team (GeoRessources, University of Lorraine), IMAR (Institute of Mathematics of the Romanian Academy) in Bucharest. We also have the support of the interdisciplinary LUE Deepsurf project (University of Lorraine).

## 4.2 Astronomy and cosmology

We have longstanding and continuous cooperation with astronomers and cosmologists in France, Spain and Estonia. In particular, we are interested in using the tools from spatial statistics to detect galaxies and

other star patterns such as filaments detection. Such developments require us to design specific point processes giving appropriate morpho-statistical distributions, as well as specific inference algorithms which are based on Monte Carlo simulation and able to handle the large volume of data.

### 4.3 Complex systems for healthcare, insurance, social networks and telecom networks

Graphs are essential to model complex systems such as the relations between agents, the spatial distribution of points that are connected such as stars, the connections in telecom networks, and so on. We develop various directions of the study of random graphs that are motivated by immediate applications:

- The success of organ transplant operations depends on their capacity to comply with real time, with sharp compatibility constraints. To improve the quality of such life-saving medical acts, we work on the optimization and control of organ transplant systems by stochastic matching models, namely, queuing models in which elements are matched in real time, following prescribed compatibility constraints.
- The modeling of epidemics, viruses on computer networks and message percolation on large social networks can be addressed using "large graph asymptotic" of random graphs. In particular, we work on Markov exploration algorithms on large Configuration Model graphs, to propose weak, but tractable approximations of such propagation phenomena on large networks.
- We have longstanding collaborations in the domain of performance analysis of telecom networks. In particular, we have pursued an intensive research activity on the modeling and analysis of queuing systems with reneging with applications to real-time networking; on the performance analysis of parallel service systems, which are a natural model for server farms and call centers, and the large-network analysis of CDMA-type (Code Division Multiple Access) communication protocols, using random graph modeling (representing the spatial interactions between agents). Telecom and peer-to-peer networks are now completed by the rise of small connected devices and the need to provide appropriate and reliable communication protocols. We also recently moved toward ad-hoc networking and the Internet of Things (IoT). Using graph theoretical and game theoretical techniques, we aim at a proper definition, and dynamical analysis, of the notion of *trust* between agents of these networks.
- Using random field models on graphs, we have considered the simulation and inference of the relations between bibliographical data related to scientific literature. This provides us with an application of our techniques in the field of dynamical evolution of networks.
- We study the spatial distribution of random T-tessellation with the aim of providing models for agricultural parcels. Again, such a problem presents challenging aspects both for simulation and inference.
- Finally, we consider personalized recommendation systems for insurance which are based on life events, using self-excited processes.

We have longstanding collaborations on these topics with Agence de Biomédecine (ABM), Le Foyer (insurance company, Luxembourg), INRAE (Avignon), Dyogene (Inria Paris), Lip 6, UTC, LORIA (computer science laboratory, Nancy), University of Buenos Aires, Northwestern University and LAAS (CNRS, Toulouse).

## 5 Highlights of the year

A. Lejay was the main organizer and member of the scientific committee of the *International Conference on Stochastic Pathwise Analysis* held online in March 2022. Initially planned to take place at CIRM (Marseille), this online conference gathered around 90 participants, including the most prominent ones, over the topic of rough paths theory, regularity structures, and various applications including ones in data sciences.

# 6 New results

## 6.1 Modeling and simulation: Fragmentation equation

**Participants:** Madalina Deaconu, Léo Gaillard, Antoine Lejay.

We have a strong interest in the fragmentation equation for understanding snow or rock avalanches. Our point of view is to explore the probabilistic representations of transport equations in this framework as well as the possibilities they offer. The underlying stochastic process represents the typical evolution of the mass of a rock or of a snow aggregate subject to successive random breakages.

In particular, we have developed in [30] the connections between various probabilistic representations of the fragmentation equation.

We have also studied a probabilistic representation of the fragmentation equation with abrasion and developed suitable numerical Monte Carlo methods. This work is performed in an on-going collaboration with Caroline Le Bouteiller (INRAE) on the topic of rock fragmentation.

With Lucian Beznea (IMAR, Bucharest) and Oana Lupaşcu-Stamate (ISMMA, Bucharest), we developed a scaling property for the continuous time fragmentation processes related to a stochastic model for the fragmentation phase of an avalanche. We highlight in this framework numerical methods based on the stochastic differential equation of fragmentation and prove the fractal property of the solution [22].

With Oana Lupaşcu-Stamate (ISMMA, Bucharest) we are developing the asymptotic behavior of an avalanche in a particular sand-pile model. This is done by combining results for discrete random processes and numerical procedures introduced in our previous works.

## 6.2 Modeling, simulation and inference: Hawkes process

**Participants:** Madalina Deaconu, Antoine Lejay, Laurent Lesage.

Hawkes processes represent a common class of self-excited stochastic processes.

We have studied the use of Hawkes processes in the context of insurance. In particular, we built a recommendation system for insurance products based on individual probabilities of life events [32]. This system is tested on the database from the insurance company Le Foyer (Luxembourg).

## 6.3 Modeling and simulation: Hitting times for stochastic differential equations

**Participants:** Madalina Deaconu.

The numerical approximation of stochastic differential equations (SDEs) and in particular new methodologies to approximate hitting times of SDEs is a challenging problem which is important for a large class of practical issues such as: geophysics, finance, insurance, biology, etc.

With Samuel Herrmann (University of Burgundy) we made progress on this topic by developing new methods for the strong convergence and pathwise approximation of one-dimensional SDEs. In particular we developed a new technique for the path approximation of one-dimensional stochastic processes, more precisely the Brownian motion and families of stochastic differential equations sharply linked to the Brownian motion (usually known as L and G-classes). We are interested here in the $\varepsilon$-strong approximation. We propose an explicit and easy to implement procedure that constructs jointly, the sequences of exit times and corresponding exit positions of some well chosen domains. We control the number of steps to cover a fixed time interval and prove the convergence theorems for our scheme. We combine here results on Brownian exit times from time-depending domains (one-dimensional heat balls) and classical renewal theory. Numerical examples and issues are also described in order to complete

the theoretical results [29]. In a recent work, we develop also similar techniques for Bessel processes of arbitrary dimension [28].

Together with Samuel Herrmann (University of Burgundy) and Cristina Zucca (University of Torino) we are working on the exact simulation of the hitting times of multi-dimensional diffusions with a grant from University of Burgundy.

### 6.4 Inference: Sticky Brownian motion

**Participants:** Alexis Anagnostakis, Antoine Lejay.

With Denis Villemonais (IECL, University of Lorraine), we constructed an estimator of the stickyness parameter of the sticky Brownian motion and other general diffusion processes from high frequency observations. This work is based on the construction of suitable estimators for the local time and the occupation time. Besides, this work provides a construction of sticky stochastic differential equations.

### 6.5 Modeling: Rough invariant embedding

**Participants:** Antoine Lejay.

With Renaud Marty (IECL, University of Lorraine), we are studying an invariant embedding problem, which consists in solving a differential equation whose initial and terminal conditions are linked by a linear relation. Using tools from the theory of rough paths, we consider Rough Differential Equations which extend ordinary differential equations driven by rough signals. In particular, we use our development in the context of equations driven by a Brownian motion while avoiding all the difficulties related to the use of anticipative stochastic calculus.

### 6.6 Inference: expansion of the maximum likelihood estimator

**Participants:** Antoine Lejay, Sara Mazzonetto.

We are studying an expansion of the maximum likilhood estimator using formal series expansions. The aim of this work is to understand the lack of Gaussianity in the non-asymptotic regime. We apply this expansion to the estimator of the skewness parameter of a skew Brownian motion, whose asymptotic mixed normality is also proved.

### 6.7 Inference: self exciting threshold Vasicek model

**Participants:** Sara Mazzonetto.

In collaboration with Paolo Pigato (University Tor Vergata, Roma) we previously studied parameter estimation for the linear drift of the self Vasicek model which follows a two-regime Ornstein-Uhlenbeck dynamic. The model fits well the behavior in financial markets related to crisis periods. In addition we provided a test for detecting the presence of two regimes and in the later months we extended our results to multiple thresholds as well. These results will improve the paper under revision [37]. After considering high frequency observations, we study new estimators for low frequency observations and the presence of several regimes.

### 6.8 Modeling and optimization: Stochastic matching models

**Participants:** Jocelyn Begeot, Thomas Masanet, Pascal Moyal.

We have made various advances in the analysis and optimization of stochastic matching models:

- In [16] we have shown, in an ongoing collaboration with Ana Busic (Dyogene, Inria Paris) and Jean Mairesse (Lip 6), that the general stochastic matching model enjoys a remarkable product form in the case where the matching policy is the natural First Come, First Matched. This result has been extended to matching models on graphs with self-loops in [11] (in the course of the PhD work of Jocelyn Begeot), in collaboration with Irène Marcovici (IECL, University of Lorraine) and Youssef Rahme (UTC). These results allow us to provide simple stability conditions for these various models, and to derive in closed form, many performance parameters at equilibrium.
- In [26], with Irène Marcovici (IECL, University of Lorraine), we provided a crucial result for the traffic control of matching models, by an exact, constructive, characterization of the stability regions of these models, namely, of the set of all stabilizable arrival rates. Using algebraic methods and flow-network theory, we also connect these rates with stationary measures of remarkable random walks on graphs. We are finally able to identify a class of compatibility graphs that make the matching rates insensitive of the matching policies, and in some cases, characterize the fairness of these models (which is an essential metric *e.g.*, in organ transplant modeling).
- In [31], in an ongoing collaboration with Matthieu Jonckheere (LAAS, Toulouse), Nahuel Soprano-Lotto (Universidad Buenos Aires) and Claudia Ramirez (Aristas), we study matching models with impatient customers, which have critical applications in matching systems in real time. We show stability conditions, control the moments of the stationary distribution and provide bounds for the speed of convergence by a Lyapunov drift analysis. Second, in ongoing works with the same co-authors, we show by extensive long-run simulations that the usual Max-Weight policies perform better in the long run, in the case of impatience, than the usually optimal GPD (Greedy Primal Dual) algorithms. In a parallel current study (ongoing PhD thesis of Thomas Masanet), we propose tools for the perfect simulations of such matching models with impatience, and in collaboration with the Agence de la Biomédecine, we propose and analyze a control of real-time organ transplants systems by pseudo-*Earliest Deadline First* policies.
- In [18], in collaboration with Youssef Rahme (UTC) we study an extension of matching models to the case of hypergraphical structures, which are relevant in applications such as assemble-to-order systems and chains of crossed organ transplant. We obtain stability conditions, and determine classes of (non-)stabilizable hypergraphs. The PhD thesis of Youssef Rahme has been defended at UTC in April 2021 [23].

### 6.9 Modeling and optimization: Parallel service systems

**Participants:** Pascal Moyal.

In an ongoing collaboration with Ohad Perry (Northwesten University, USA), we have obtained (in-)stability criteria for parallel service systems with routing errors. These models have applications in the optimization of large call centers and server farms. These results have been published in [17].

### 6.10 Modeling and optimization: Maximal coupling on large random graphs

**Participants:** Madalina Deaconu, Antoine Lejay, Pascal Moyal.

In an ongoing collaboration with Mohamed Habib Diallo Aoudi and Vincent Robin (UTC), we have proposed a Markov exploration algorithm, coupled with the construction of the Configuration model, to represent a coupling algorithm on a large random graph, which is a typical model for *e.g.*, dating websites and online advertisement. We obtain a tractable estimate of the matching coverage via fluid approximation, the accuracy of which is illustrated by extensive simulations, for various graph degree distributions. These results can be found in the submitted paper [25].

Following the research internship of Nicolas Lengert (now at University of Luxembourg) in 2020, we also investigate the dual approach of stochastic matching as the construction of maximal couplings in large labelled random graphs generated from a root compatibility graph.

### 6.11 Modeling and inference: speed of convergence in functional central limit theorems

**Participants:** Pascal Moyal.

In an ongoing collaboration with Eustache Besançon (Telecom Paristech), Laurent Decreusefond (Telecom Paristech) and Laure Coutin (Université Paul Sabatier), we investigate the speed of convergence in the functional Central Limit Theorem for Continuous Time Markov Chains (CTMC), by using stochastic analysis tools (Malliavin calculus and the Stein method). These results allow us to characterize the accuracy (and thereby the confidence interval) in diffusion approximations of many practical processes, as shown in the submitted paper [27].

### 6.12 Inference and simulation: Shadow Simulated Annealing: a new algorithm to approximate Bayesian inference of Gibbs point processes

**Participants:** Madalina Deaconu, Radu Stoica.

In a collaboration with Anne Philippe (University of Nantes) and Lluis Hurtado-Gil (UPM, Madrid), we developed in [19] a new algorithm for statistical inference and analysis of spatial patterns assumed to be realizations of Gibbs point processes. This approach has a general character and it contributes to the existing methods based on Approximate Bayesian Computation, by providing control properties of the proposed solution. Results on simulated data and real data are presented. The real data application fits an inhomogeneous area interaction point process to cosmological data. The obtained results validate two important aspects of the galaxy distribution in our universe: proximity of the galaxies from the cosmic filament network; and the territorial clustering at a given range of interaction.

### 6.13 Modeling and inference: Morphostatistical characterization of the spatial galaxy distribution through Gibbs point processes

**Participants:** Radu Stoica.

In a cooperation with Lluis Hurtado-Gil (UPM, Madrid), and Vincent Martinez and Pablo Arnalte Mur (Observatori Astronòmic de la Universitat de València) we propose in [13] a morphostatistical characterization of the galaxy distribution through spatial statistical modeling based on inhomogeneous Gibbs point processes. The galaxy distribution is supposed to exhibit two components. The first one is related to the major geometrical features exhibited by the observed galaxy field, here, its corresponding filamentary pattern. The second one is related to the interactions exhibited by the galaxies. Gibbs point processes are statistical models able to integrate these two aspects in a probability density, controlled by some parameters. Several such models are fitted to real observational data via the ABC shadow algorithm. This

algorithm provides simultaneous parameter estimation and posterior-based inference, hence allowing the derivation of the statistical significance of the obtained results.

### 6.14 Modeling and inference: an application of neural point processes to geophysical data

**Participants:** Pierre-Alexandre Simon, Radu Stoica.

The huge amount of temporal data available nowadays in numerous scientific fields requires dedicated analysis and prediction methods. Stochastic temporal point processes are certainly one of the popular approaches available to model time series. While point processes have been successfully applied in many application domains, they need strong assumptions. For instance, the conditional intensity is often supposed to follow a particular parametric function, hence fixing *a priori* the structure of the event distribution: purely random or independent, clustered or regular. Recent papers investigate the use of models from machine learning dedicated to sequential event analysis, namely recurrent neural networks (RNN). These RNNs are expected to be versatile enough to automatically adapt to the data, without the need for *a priori* choosing the character of the event distribution. This work presents an introduction to the so-called neural point processes and discusses numerical experiments. In particular, the presented real data application considers seismic data from the Guadeloupe region.

This work was done during the internship of P.-A. Simon, co-directed by R. Stoica and F. Sur (Tangram project-team, Inria NGE). The paper was presented in the conference RING 2021 [20].

### 6.15 Modeling and inference: Estimation of singular diffusions

**Participants:** Alexis Anagnostakis, Sara Mazzonetto.

We are extending our respective results on high frequency approximation of the local time of oscillating-skew-sticky diffusion processes. The purpose is to estimate the parameters and to model some critical behavior in financial markets related to crisis periods.

### 6.16 Modeling and simulation: Navier Stokes equation - stochastic modeling

**Participants:** Madalina Deaconu.

With Lucian Beznea (IMAR, Bucharest) and Oana Lupaşcu-Stamate (ISMMA, Bucharest) we are developing a stochastic approach for the two-dimensional Navier Stokes equation in a bounded domain. More precisely we consider the vorticity equation and construct a specific non-local branching process. This approach is new and can conduct to important advances as it will give also a new numerical algorithm if successful.

## 7 Partnerships and cooperations

### 7.1 International initiatives

#### 7.1.1 Participation in other International Programs

**Participants:** Antoine Lejay, Pascal Moyal.

**Title:** Biostochastic Research Network

**Funding:** Conicyt Chile

**International Partner (Institution - Laboratory - Researcher):**

- Universidad de Valparaiso (Chile) - CIMFAV – Facultad de Ingenieria - Soledad Torres, Rolando Rebolledo
- CNRS, Inria & IECL - Institut Élie Cartan de Lorraine (France) - N. Champagnat, A. Lejay (coordinator for France), D. Villemonnais, R. Schott.

**Duration:** April 2018 - April 2022

**Goal:** scientific exchange around probabilistic models in population ecology.

**Title:** EnhanceD Data stream Analysis (EDDA)

**Program:** ANR call IA ANR-DFG-JST

**International Partner (Institution - Laboratory - Researcher):**

- Japan Agency for Marine-Earth Science and Technology (Japan)
- University of Greifswald (Germany)
- CNRS, Inria & IECL - Institut Élie Cartan de Lorraine (France) - M. Clausel (coordinator for France), A. Lejay.

**Duration:** Dec 2019 - Dec 2022

**Goal:** Develop new machine learning techniques based on signature methods and iterated integrals.

**Title:** Matching architectures that connect heterogeneous users and efficient healthcare systems (MATCHES)

**Program:** ANR PRC

**International Partner (Institution - Laboratory - Researcher):**

- Northwestern University (USA)
- UC London Business School (UK)
- University of Buenos Aires (Argentina)
- Agence de la Biomédecine, Lip 6, LORIA, UTC & IECL - Institut Élie Cartan de Lorraine (France) - P. Moyal (coordinator).

**Duration:** Nov 2018 - Apr 2023

**Goal:** Stochastic analysis, optimization and control of matching algorithms on graphs, connecting incoming users under random traffic contraints. Applications to Healthcare systems, organ transplants, peer-to-peer networking and collaborative economy.

#### 7.1.2 Visits of international scientists

Lucian Beznea (IMAR Bucharest) visited the Pasta team for two weeks in September.

### 7.2 National initiatives

**Participants:** Alexis Anagnostakis, Madalina Deaconu, Sara Mazzonetto.

- A. Anagnostakis and S. Mazzonetto applied successfully to BOUM project from SMAI to sponsor the organization of a meeting with the purpose of increasing a network of young researchers on singular diffusions.
- Since October 2020, M. Deaconu is developing with S. Herrmann (University of Burgundy) and C. Zucca (University of Torino), a BQR project, funded by the University of Burgundy, on the *Exact simulation of the exit time of a bounded domain for a random process*.

## 8 Dissemination

**Participants:** Madalina Deaconu, Antoine Lejay, Sara Mazzonetto, Pascal Moyal, Radu Stoica.

### 8.1 Promoting scientific activities

#### 8.1.1 Scientific events: organisation

**General chair, scientific chair**

- M. Deaconu, as head of the Fédération Charles Hermite, organized 5 scientific one-day meetings on interdiciplinary topics.
- A. Lejay was the leader of the organization and scientific committee of the international conference *Pathwise Stochastic Analysis and Applications* (CIRM, Marseille, France) in March 2021.
- A. Lejay co-organized with V. Chevrier (LORIA, University of Lorraine) a one-day meeting of *Fédération Charles Hermite* on the topic *IA and energy* (online) in February 2021.
- A. Lejay and P. Moyal co-organized with Gilles Millérioux (CRAN, University of Lorraine) two one-day meetings of *Fédération Charles Hermite* on the topic *Networks sciences* (IECL, Nancy, France) in October and November 2021.
- P. Moyal organized the second scientific workshop of the ANR project MATCHES *Stochastic matching models and their applications* (IECL, Nancy, France) in December 2021.
- P. Moyal is the chief organizer of the forthcoming conference Informs APS 2023 (to be held in Nancy, France - initially scheduled in 2021 and postponed due to COVID). He is coordinating the ongoing works of the Scientific Committee and the Organizing Committee.
- M. Deaconu co-organized with Francisco Bernal (University Carlos III, Madrid) the Minisymposium *Numerical Methods for SDEs with Boundary Issues*, 13th International Conference on Monte Carlo Methods, MCM 2021, 16-20 August 2021 (online), Mannheim.
- A. Lejay co-organized with Ernesto Mordecki (Universidad República, Uruguay) and Paavo Salminen (Åbo Akademi, Finland) a session *Stochastic analysis and stochastic processes* at the VI Congreso Latinoamericano de Matemáticos, CLAM (initially in 2020, online) in September 2021.
- R. Stoica was chairman of a session for *Workshop on Spatial Statistics and Image Analysis in Biology* (Helsinki, 2021).

**Member of the conference program committees**

- M. Deaconu and A. Lejay are members of the Scientific Committee of the forthcoming conference Informs 2023 (to be held in Nancy - France, see above), and take part of the ongoing work of scientific organization.
- A. Lejay was a member of the scientific committee of the National Conference *Journées de Probabilités 2021* (Guidel, France) in June 2021.
- R. Stoica was a member of the scientific committee for *Deepsurf Conference: toward solutions for energy and ecological transition* (Nancy, 2021).

### 8.1.2 Journal

**Member of the editorial boards**

- A. Lejay is one of the three Editors of *Séminaire de Probabilités* (since 2010).
- A. Lejay is Associate Editor of *Mathematics and Computers in Simulation* (MATCOM), the journal of the IMACS society (since 2017).
- R. Stoica is Associate Editor of *Annals of the Institute of Statistical Mathematics* (since 2019).
- R. Stoica is member of the editorial board of *Spatial Statistics Journal* (since 2015).
- P. Moyal is Associate Editor of *Queueing systems: Theory and applications* (since 2018).

**Reviewer - reviewing activities**

- M. Deaconu wrote reviews for *Methodology and Computing in Applied Probability*, *Journal of Statistical Physics*, and *Numerical Algorithms NUMA-D*.
- A. Lejay wrote reviews for *Advances in Computational Mathematics*, *AIMS Mathematics*, *Annals of Applied Probability*, *Applied Probability Journals*, *Journal of Functional Analysis*, *Numerical algorithms*, *Physica A*, *Physical Review E*, and *Transactions on Modeling and Computer Simulation*.
- S. Mazzonetto wrote a review report for *Journal of Computational and Applied Mathematics*.
- P. Moyal wrote review reports for *Annals of Applied Probability*, *Queueing systems: Theory and applications*, *Operations Research*, *Stochastic processes and their applications* and *Mathematics of Operations research*.

### 8.1.3 Invited talks

- A. Lejay gave a short lecture at *Young researchers between geometry and stochastic analysis 2021*(online, University Adger, Kristiansand, Norway) in June 2021.
- A. Lejay gave a talk at the national conference *Master Class Masterkesm: From kinetic equations to statistical mechanics* (St-Jean-de-Monts, France) in June 2021.
- A. Lejay gave a seminar talk at the *Differential equations and Numerical Analysis (DNA) group*, NTNU (Norway) in February 2021.
- R. Stoica gave a talk at *Workshop Orano Data Science*, University of Lorraine, 2021
- R. Stoica gave a seminar talk at *IMAR - Séminaire de Statistique*, University of Strasbourg, 2021
- R. Stoica gave a seminar talk at *Lab. P. Painlevé - Stochastic Geometry working group*, University of Lille, 2021

#### 8.1.4 Leadership within the scientific community

- M. Deaconu is the head of the *Fédération Charles Hermite*, within CNRS and University of Lorraine, including three research laboratories: CRAN (control theory), IECL (mathematics) and LORIA (computer science).
- M. Deaconu is member of the Scientific Committee of the CNRS GdR MathGéoPhys in mathematics in interaction with geophysics.
- A. Lejay is the head of *Probability and Statistics Team* of Institut Élie Cartan de Lorraine (IECL).
- A. Lejay is leader of the GdR TRAG a national research network on rough paths analysis (funded by CNRS-Insmi).

#### 8.1.5 Scientific expertise

- R. Stoica was evaluating a project for University of Toronto Data Science Institute.

#### 8.1.6 Research administration

- M. Deaconu and A. Lejay are members of the Conseil du Pôle AM2I (University of Lorraine) and of the Conseil IECL.
- M. Deaconu is a member of the *Bureau des Comité des Projets* at Inria NGE.
- M. Deaconu was a member of the hiring committee for a associate professor position at University of Avignon.
- M. Deaconu was a member of the hiring committee for a associate professor position at IECL, University of Lorraine.
- A. Lejay represents Inria NGE within the board of AMIES.
- A. Lejay is a member of the Executive board of LUE Impact project DigiTrust (University of Lorraine).
- A. Lejay is a member of the board of AMIES (Agence pour les Mathématiques en Interaction avec l'Entreprise et la Société, Labex CNRS-UGA-Inria).
- A. Lejay is member of the CUMI of Inria NGE.
- A. Lejay and P. Moyal participated to the hiring committee for a full professor position at IECL, University of Lorraine (Metz).
- R. Stoica is a nominated member of the Conseil IECL and responsible of the international relations of IECL.
- R. Stoica is a member of the Executive board of LUE Impact project Deepsurf (University of Lorraine).
  - co-responsible of the scientifc axis "Interaction profond surface"
  - co-responsible of the work package "Approches mathématiques des phénomènes de transfert".
  - R. Stoica was the president of the hiring committee for a associate professor position at IECL, University of Lorraine.

## 8.2 Teaching - Supervision - Juries

### 8.2.1 Teaching

S. Mazzonetto is assistant professor, P. Moyal and R. Stoica are professors. They have full teaching duties with lectures at all the levels of the university. We mention here only lectures at master 1 and master 2 levels as well as responsabilities.

- M. Deaconu, *Stochastic Modeling*, 30h, M2, Master IMSD, University of Lorraine.
- M. Deaconu, *Stochastic Differential Equations: Numerical Methods and Applications*, 21h, M2, Ecole des Mines de Nancy, University of Lorraine.
- M. Deaconu, *Random Variable simulation*, 12h, M1, Ecole des Mines de Nancy, University of Lorraine.
- A. Lejay, *Simulation des marchés financiers*, 29h, M2, Master PSA, University of Lorraine.
- A. Lejay, *Régression*, 40h, M2, Master IMDS, University of Haute-Alsace, Mulhouse.
- S. Mazzonetto, Statistics, 22h, M1, ENSEM, Universiy of Lorraine.
- S. Mazzonetto, Probability and Statistics, 40h, M1, Master IMSD and MFA, Universiy of Lorraine.
- P. Moyal is the head of the Master M2 IMSD *Ingénierie Mathématique et Science des Données* (University of Lorraine).
- P. Moyal, Financial mathematics, 25h, M2, Master IMSD, University of Lorraine.
- P. Moyal, Stochastic financial modeling, 45h, M2, Master IMSD, University of Lorraine.
- P. Moyal, Stochastic networks, 20h, M2, Master IMSD, University of Lorraine
- P. Moyal, Applied linear algebra, 25h, M1, Master IMSD, University of Lorraine.
- R. Stoica, Simulation and Inference via Monte Carlo Methods, 28h, M1, Master IMSD, University of Lorraine.
- R. Stoica, Spatial Statistics and Bayesian Inference, 36h, M2, Master IMSD, University of Lorraine.

### 8.2.2 Supervision

- PhD (defended): Youssef Rahme, *Stochastic matching models on general structures*, Université Technologique de Compiègne, defended in April 2021, P. Moyal [23].
- PhD in progress: Alexis Anagnostakis, *Étude du mouvement brownien collant*, University of Lorraine, October 2018, University of Lorraine grant, A. Lejay and D. Villemonais.
- PhD in progress: Jocelyn Begeot, *Perfect simulation of infinite-state space Markov chains*, University of Lorraine, October 2019, University of Lorraine grant, I. Marcovici and P. Moyal.
- PhD in progress: Mohamed Habib Diallo Aoudi, *Online Coupling algorithm in large random graph*, UTC, January 2018, funding LMAC, P. Moyal and V. Robin.
- PhD in progress: Laurent Lesage, *Data Analysis for Insurance*, University of Luxembourg and University of Lorraine, September 2018, funding Le Foyer, M. Deaconu and R. State.
- PhD in progress: Thomas Masanet, *Stochastic matching models with impatience, and applications to organ transplant networks*, University of Lorraine, October 2019, grant ANR / Région Grand Est, C. Jacquelinet and P. Moyal.
- PhD in progress: Christophe Reype, *Simultaneous parameter estimation and pattern detection in spatial data. Applications to the analysis of the dynamic in multi-component fluid mixtures in Geology*, University of Lorraine, October 2019, LUE grant, M. Deaconu and R. Stoica.

- PhD in progress: Runbo Su, *Mathematical modeling of the trust relationship in the Internet of Things*, University of Lorraine, October 2020, funding ANR / Fédération Charles Hermite / LORIA, P. Moyal, E. Natalizio and Y-Q. Song.
- PhD in progress: Fabrice Taty-Moukati, *Stochastic seismic structural interpretation of geological faults*, University of Lorraine, March 2021, RING grant, G. Caumon and R. Stoica.

#### 8.2.3 Juries

- M. Deaconu was a reviewer for the PhD thesis of Youssef Rahmé, UTC, defended in April 2021.
- M. Deaconu was an examinator in the PhD committee of Nicolas Massin (University of Burgundy), defended in March 2021.
- A. Lejay was a reviewer for the PhD theses of Soufiane Mouchtabih (University of Toulon and University of Marrakech, defended in March 2023), of Leonardo Andrès Videla Moñoz (Consorcio UV-PUCV-USM, Chile, defended in March 2023) and of Nicolas Massin (University of Burgundy, defended in March 2023).
- A. Lejay was a member of the committe of the *challenge doctorants* organized by AMIES.
- P. Moyal was a reviewer for the PhD thesis of A. Cadas (ENS / Inria).
- R. Stoica was a reviewer for the PhD thesis of Tony Bonnaire (University Paris Saclay).

### 8.3 Popularization

#### 8.3.1 Creation of media or tools for science outreach

A. Lejay is a editor of the project Success Stories (AMIES and FSMP) dedicated to create 2-page sheets that present successful collaborations between industry and academia.

#### 8.3.2 Articles and contents

M. Deaconu gave an interview at the France Embassy in Bucharest and to the *Institut Français de Roumanie* – for the action Women in Sciences, 12 February 2021.

#### 8.3.3 Education

S. Mazzonetto participated in the organization of the exhibition “les mathématiques se conjuguent aussi au féminin”.

## 9 Scientific production

### 9.1 Major publications

[1] L. Beznea, M. Deaconu and O. Lupascu. ‘Stochastic equation of fragmentation and branching processes related to avalanches’. In: *Journal of Statistical Physics* 162.4 (8th Feb. 2016), pp. 824–841. DOI: 10.1007/s10955-015-1432-5. URL: https://hal.inria.fr/hal-01216137.

[2] M. Deaconu and S. Herrmann. ‘Initial-boundary value problem for the heat equation - A stochastic algorithm’. In: *Annals of Applied Probability* 28.3 (2018), pp. 1943–1976. DOI: 10.1214/17-AAP1348. URL: https://hal.archives-ouvertes.fr/hal-01380365.

[3] A. Hudde, M. Hutzenthaler and S. Mazzonetto. ‘A stochastic Gronwall inequality and applications to moments, strong completeness, strong local Lipschitz continuity, and perturbations’. In: *Annales de l’Institut Henri Poincaré, Probabilités et Statistiques* 57.2 (1st May 2021). DOI: 10.1214/20-AIHP1064. URL: https://hal.archives-ouvertes.fr/hal-03293250.

[4] A. Lejay. 'Constructing general rough differential equations through flow approximations'. In: *Electronic Journal of Probability* 27 (2021), pp. 1–24. DOI: 10.1214/21-EJP717. URL: https://hal.inria.fr/hal-02871886.

[5] A. Lejay and P. Pigato. 'Statistical estimation of the Oscillating Brownian Motion'. In: *Bernoulli* 24.4B (2018), pp. 3568–3602. DOI: 10.3150/17-BEJ969. URL: https://hal.archives-ouvertes.fr/hal-01430794.

[6] S. Mazzonetto. *Rates of convergence to the local time of Oscillating and Skew Brownian Motions*. 6th Oct. 2021. URL: https://hal.archives-ouvertes.fr/hal-03367822.

[7] P. Moyal, A. Bušić and J. Mairesse. 'A product form for the general stochastic matching model'. In: *Journal of Applied Probability* 58.2 (June 2021), pp. 449–468. DOI: 10.1017/jpr.2020.100. URL: https://hal.archives-ouvertes.fr/hal-03294756.

[8] Y. Rahme and P. Moyal. 'A stochastic matching model on hypergraphs'. In: *Advances in Applied Probability* 53.4 (2021), pp. 951–980. DOI: 10.1017/apr.2021.8. URL: https://hal.archives-ouvertes.fr/hal-03294780.

[9] C. Reype, A. Richard, M. Deaconu and R. S. Stoica. 'Bayesian statistical analysis of hydrogeochemical data using point processes: a new tool for source detection in multicomponent fluid mixtures'. In: RING Meeting 2020. Nancy, France, 7th Sept. 2020. URL: https://hal.archives-ouvertes.fr/hal-02933268.

[10] R. Stoica, M. Deaconu, A. Philippe and L. Hurtado-Gil. 'Shadow Simulated Annealing: A new algorithm for approximate Bayesian inference of Gibbs point processes'. In: *Spatial Statistics* (10th Apr. 2021). DOI: 10.1016/j.spasta.2021.100505. URL: https://hal.archives-ouvertes.fr/hal-02183506.

## 9.2 Publications of the year

**International journals**

[11] J. Begeot, I. Marcovici, P. Moyal and Y. Rahme. 'A general stochastic matching model on multigraphs'. In: *ALEA : Latin American Journal of Probability and Mathematical Statistics* 18.2 (June 2021), pp. 1325–1351. DOI: 10.30757/ALEA.v18-49. URL: https://hal.archives-ouvertes.fr/hal-03168254.

[12] A. Brault and A. Lejay. 'The non-linear sewing lemma II: Lipschitz continuous formulation'. In: *Journal of Differential Equations* 293 (25th Aug. 2021), pp. 482–519. DOI: 10.1016/j.jde.2021.05.020. URL: https://hal.inria.fr/hal-01839202.

[13] L. Hurtado-Gil, R. S. Stoica, V. Martínez and P. Arnalte-Mur. 'Morphostatistical characterization of the spatial galaxy distribution through Gibbs point processes'. In: *Monthly Notices of the Royal Astronomical Society* 507.2 (2021), pp. 1710–1722. DOI: 10.1093/mnras/stab2268. URL: https://hal.archives-ouvertes.fr/hal-03224715.

[14] A. Lejay. 'Book Review: a Course on Rough Paths - With an Introduction to Regularity Structures (Peter K. Friz and Martin Hairer)'. In: *Bulletin of the American Mathematical Society* (2021). URL: https://hal.inria.fr/hal-03475899.

[15] A. Lejay. 'Constructing general rough differential equations through flow approximations'. In: *Electronic Journal of Probability* 27 (2021), pp. 1–24. DOI: 10.1214/21-EJP717. URL: https://hal.inria.fr/hal-02871886.

[16] P. Moyal, A. Bušić and J. Mairesse. 'A product form for the general stochastic matching model'. In: *Journal of Applied Probability* 58.2 (June 2021), pp. 449–468. DOI: 10.1017/jpr.2020.100. URL: https://hal.archives-ouvertes.fr/hal-03294756.

[17] P. Moyal and O. Perry. 'Stability of Parallel Server Systems'. In: *Operations Research* (2021). DOI: 10.1287/opre.2021.2125. URL: https://hal.archives-ouvertes.fr/hal-03294778.

[18] Y. Rahme and P. Moyal. 'A stochastic matching model on hypergraphs'. In: *Advances in Applied Probability* 53.4 (2021), pp. 951–980. DOI: 10.1017/apr.2021.8. URL: https://hal.archives-ouvertes.fr/hal-03294780.

[19] R. Stoica, M. Deaconu, A. Philippe and L. Hurtado-Gil. 'Shadow Simulated Annealing: A new algorithm for approximate Bayesian inference of Gibbs point processes'. In: *Spatial Statistics* (10th Apr. 2021). DOI: 10.1016/j.spasta.2021.100505. URL: https://hal.archives-ouvertes.fr/hal-02183506.

**International peer-reviewed conferences**

[20] P.-A. Simon, R. S. Stoica and F. Sur. 'An application of neural point processes to geophysical data'. In: RING Meeting 2021. Nancy, France, 6th Sept. 2021, pp. 1–13. URL: https://hal.archives-ouvertes.fr/hal-03294911.

[21] R. Su, A. R. Sfar, E. Natalizio, P. Moyal and Y.-Q. Song. 'PDTM: Phase-based dynamic trust management for Internet of things'. In: ICCCN 2021 - 30th International Conference on Computer Communications and Networks. Athens/Virtual, Greece: IEEE, 19th July 2021, pp. 1–7. DOI: 10.1109/ICCCN52240.2021.9522234. URL: https://hal.archives-ouvertes.fr/hal-03322831.

**Scientific book chapters**

[22] L. Beznea, M. Deaconu and O. Lupaşcu-Stamate. 'Scaling property for fragmentation processes related to avalanches'. In: *Applications of Mathematics and Informatics in Natural Sciences and Engineering*. Vol. Applications of Mathematics and Informatics in Natural Sciences and Engineering AMINSE 2019, Tbilisi, Georgia, September 23–26. Springer Proceedings in Mathematics & Statistics 334. Springer, 1st Jan. 2021. DOI: 10.1007/978-3-030-56356-1_3. URL: https://hal.archives-ouvertes.fr/hal-02942710.

**Doctoral dissertations and habilitation theses**

[23] Y. Rahmé. 'Stochastic matching model on the general graphical structures'. Université de Technologie de Compiègne, 8th Apr. 2021. URL: https://hal.archives-ouvertes.fr/tel-03212765.

**Reports & preprints**

[24] A. Anagnostakis. *Functional convergence to the local time of sticky diffusions*. 1st Feb. 2022. URL: https://hal.inria.fr/hal-03551808.

[25] M. H. A. D. Aoudi, P. Moyal and V. Robin. *Markovian online matching algorithms on large bipartite random graphs*. 21st July 2021. URL: https://hal.archives-ouvertes.fr/hal-03294781.

[26] J. Begeot, I. Marcovici and P. Moyal. *Stability regions of systems with compatibilities, and ubiquitous measures on graphs*. 25th Nov. 2021. URL: https://hal.archives-ouvertes.fr/hal-03450251.

[27] E. Besançon, L. Coutin, L. Decreusefond and P. Moyal. *Diffusive limits of Lipschitz functionals of Poisson measures*. 12th July 2021. URL: https://hal.telecom-paris.fr/hal-03283778.

[28] M. Deaconu and S. Herrmann. *Strong approximation of Bessel processes*. 1st June 2021. URL: https://hal.archives-ouvertes.fr/hal-03244538.

[29] M. Deaconu and S. Herrmann. *Strong approximation of particular one-dimensional diffusions*. 7th June 2021. URL: https://hal.archives-ouvertes.fr/hal-02799638.

[30] M. Deaconu and A. Lejay. *Probabilistic representations of fragmentation equations*. 16th Dec. 2021. URL: https://hal.inria.fr/hal-03483448.

[31] M. Jonckheere, P. Moyal, C. Ramírez and N. Soprano-Loto. *Generalized max-weight policies in stochastic matching*. 26th Sept. 2021. URL: https://hal.archives-ouvertes.fr/hal-03354805.

[32] L. Lesage, M. Deaconu, A. Lejay, J. A. Meira, G. Nichil and R. State. *A Recommendation System For Insurance Built With A Multivariate Hawkes Process Based On Customers' Life Events*. 16th Dec. 2021. URL: https://hal.archives-ouvertes.fr/hal-03483812.

[33] Z. Liu, M. Perrodin, T. Chambrion and R. S. Stoica. *Windowed total variation denoising and noise variance monitoring*. 27th Jan. 2021. URL: https://hal.archives-ouvertes.fr/hal-03122844.

[34] J. Mairesse and P. Moyal. *New frontiers for stochastic matching*. 8th Feb. 2022. URL: https://hal.archives-ouvertes.fr/hal-03561106.

[35] T. Masanet and P. Moyal. *Perfect sampling of stochastic matching models with reneging*. 25th Feb. 2022. URL: https://hal.archives-ouvertes.fr/hal-03580942.

[36] S. Mazzonetto. *Rates of convergence to the local time of Oscillating and Skew Brownian Motions*. 6th Oct. 2021. URL: https://hal.archives-ouvertes.fr/hal-03367822.

[37] S. Mazzonetto and P. Pigato. *Drift estimation of the threshold Ornstein-Uhlenbeck process from continuous and discrete observations*. 21st July 2021. URL: https://hal.archives-ouvertes.fr/hal-03293542.

[38] P. Moyal and O. Perry. *Many-server limits for service systems with dependent service and patience times*. 8th Feb. 2022. URL: https://hal.archives-ouvertes.fr/hal-03561126.

[39] R. Su, A. Riahi Sfar, E. Natalizio, P. Moyal and Y.-Q. Song. *SOPHT: a PHase-based Trust management framework for Service-Oriented IoT/IIoT*. Loria, 10th Feb. 2022. URL: https://hal.archives-ouvertes.fr/hal-03363098.