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2025 *Activity Report*

RESEARCH CENTRE: **Inria Paris Centre at Sorbonne University**
IN PARTNERSHIP WITH: **CNRS, Sorbonne Université**

Project-Team

COMMEDIA

Computational mathematics for bio-medical applications

In collaboration with Laboratoire Jacques-Louis Lions (LJLL)

Project-Team COMMEDIA

Creation of the Project-Team: 2019 June 01

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

Keywords

Computer sciences and digital sciences

A6.1.1. – Continuous Modeling (PDE, ODE)

A6.1.4. – Multiscale modeling

A6.1.5. – Multiphysics modeling

A6.2.1. – Numerical analysis of PDE and ODE

A6.3.1. – Inverse problems

A6.3.2. – Data assimilation

A6.3.4. – Model reduction

Other research topics and application domains

B2.2.1. – Cardiovascular and respiratory diseases

B2.4.1. – Pharmaco kinetics and dynamics

Contents

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2 Overall objectives

COMMEDIA is a joint project-team of the Inria Research Center of Paris and the Jacques-Louis Lions Laboratory (LJLL) of Sorbonne Université and CNRS (UMR7598). The research activity of COMMEDIA focuses on the numerical simulation of bio-fluid flows in the human body, more specifically, blood flows in the cardiovascular system and air flows in the respiratory system. These simulations are intended to complement available clinical data with the following purpose: help clinicians or bio-engineers to enhance the understanding of physiological phenomena, to improve diagnosis and therapy planning or to optimize medical devices. The main objectives of COMMEDIA are:

- the development of appropriate mathematical models and efficient numerical methods for the simulations and for the interaction of simulations with measured data;
- the mathematical analysis of these models and numerical techniques;
- the development and validation of scientific computing software which implements these numerical techniques.

A distinctive feature of the mathematical models considered in COMMEDIA is that they often couple different types of partial differential equations (PDEs). This heterogeneous character in the models is a mathematical manifestation of the multi-physics nature of the considered problems.

3 Research program

3.1 Multi-physics modeling and simulation

The research activity in terms of modeling and simulation (i.e., the so-called forward problem) is driven by two application domains related to the cardiovascular and the respiratory systems.

3.1.1 Cardiovascular hemodynamics

We distinguish between *cardiac hemodynamics* (blood flow inside the four chambers of the heart) and *vascular hemodynamics* (blood flow in the vessels of the body).

Cardiac hemodynamics. The numerical simulation of cardiac hemodynamics presents many difficulties. We can mention, for instance, the large deformation of the cardiac chambers and the complex fluid-structure interaction (FSI) phenomena between blood, the valves and the myocardium. Blood flow can be described by the incompressible Navier-Stokes equations which have to be coupled with a bio-physical model of the myocardium electro-mechanics and a mechanical model of the valves. The coupling between the fluid and the solid media is enforced by kinematic and dynamic coupling conditions, which guarantee the continuity of velocity and stresses across the interface. In spite of the significant advances achieved since the beginning of this century (see, e.g., [62, 63, 60, 65, 53]), the simulation of all the fluid-structure interaction phenomena involved in the heart hemodynamics remains a complex and challenging problem.

Heart valves are definitely a bottleneck of the problem, particularly due to their fast dynamics and the contact phenomena with high pressure-drops. Computational cost is recognized as one of the key difficulties, related to the efficiency of the FSI coupling method and the robustness of the contact algorithm. Furthermore, the numerical discretization of these coupled systems requires to deal with unfitted fluid and solid meshes, which are known to complicate the accuracy and/or the robustness of the numerical approximations (see Section 3.3.2 below).

The ultimate goal of the proposed research activity is the simulation of the complete fluid-structure-contact interaction phenomena involved within the heart. Most of this work will be carried out in close collaboration with the M3DISIM project-team, which has a wide expertise on the modeling, simulation and estimation of myocardium electro-mechanics. We will also consider simplified approaches for cardiac hemodynamics (see, e.g., [35, 48, 51]). The objective is to develop mathematically sound models of reduced valve dynamics with the purpose of enhancing the description of the pressure dynamics right after the opening/closing of the valve (traditional models yield spurious pressure oscillations).

Vascular hemodynamics. The modeling and simulation of vascular hemodynamics in large vessels has been one of the core research topics of some members of COMMEDIA, notably as regards the fluid-structure interaction phenomena. Here we propose to investigate the modeling of pathological scenarios, such as the hemorrhage phenomena in smaller vessels. Modeling of hemorrhage is motivated by the medical constatation that, after a primary vessel wall rupture, secondary vessel wall ruptures are observed. Biologists postulate that the mechanical explanation of this phenomenon might be in the change of applied stress due to blood bleeding. We propose to model and simulate the underlying coupled system, blood vessel flow through the external tissue, to estimate the effect of the subsequent stress variation.

3.1.2 Respiratory flows

The motivation of the proposed research activities is to develop a hierarchy of easily parametrizable models allowing to describe and efficiently simulate the physical, mechanical and biological phenomena related to human respiration, namely, ventilation, particle deposition, gas diffusion and coupling with the circulatory system.

Ventilation. The current modeling approaches (either 3D–0D coupled models where the 3D Navier-Stokes equations are solved in truncated geometries of the bronchial tree with appropriate lumped boundary conditions, or 0D–3D coupled models where the lung parenchyma is described by a 3D elastic media irrigated by a simplified bronchial tree) provide satisfactory results in the case of mechanical ventilation or normal breathing. Realistic volume-flow phase portraits can also be simulated in the case of forced expiration (see [37, 45, 68]), but the magnitude of the corresponding pressure is not physiological. The current models must be enriched since they do not yet correctly describe all the physiological phenomena at play. We hence propose to extend the 0D–3D (bronchial tree–parenchyma) model developed in the team, by considering a non-linear, viscoelastic and possibly poro-elastic description of the parenchyma with appropriate boundary conditions that describe ribs and adjacent organs and taking into account an appropriate resistive model.

So far, the motion of the trachea and proximal bronchi has been neglected in the ventilation models (see, e.g., [70]). These features can be critical for the modeling of pathologic phenomena such as sleep apnea and occlusion of the airways. This would be a long-term goal where fluid-structure interaction and the possible contact phenomena will be taken into account, as in the simulation of cardiac hemodynamics (see Section 3.1.1).

Aerosol and gas diffusion. The dynamics of aerosols in the lung have been widely studied from the mathematical modeling standpoint. They can be described by models at different scales: the microscopic one for which each particle is described individually, the mesoscopic (or kinetic) one for which a density of probability is considered, or the macroscopic one where reaction-diffusion equations describing the behavior of the constituant concentration are considered. The objective of COMMEDIA will mainly be to develop the kinetic approach that allows a precise description of the deposition area at controlled computational costs. Part of this study could be done in collaboration with colleagues from the Research Center for Respiratory Diseases at Inserm Tours (UMR1100).

The macroscopic description is also appropriate for the diffusion of gases (oxygen and carbon dioxide) in the bronchial tree (see [64]). Regarding the influence of the carrier gas, if the patient inhales a different mixture of air such as a Helium-Oxygen mixture, the diffusion mechanisms could be modified. In this context, the goal is to evaluate if the cross-diffusion (and thus the carrier gas) modifies the quantities of oxygen diffused. Part of this work will be carried out in collaboration with members of the LJLL and of the MAP5.

As a long term goal, we propose to investigate the coupling of these models to models of diffusion in the blood or to perfusion models of the parenchyma, and thus, have access thanks to numerical simulations to new indices of ventilation efficiency (such as dissolved oxygen levels), depending on the pathology considered or the resting or exercise condition of the patient.

3.2 Simulation with data interaction

The second research axis of COMMEDIA is devoted to the interaction of numerical simulations with measured data. Several research directions related to two specific applications are described below: blood flows and cardiac electrophysiology, for which the mathematical models have been validated against experimental data. This list is not exhaustive and additional problems (related to cardiac and respiratory flows) shall be considered depending on the degree of maturity of the developed models.

3.2.1 Fluid flow reconstruction from medical imaging

A first problem which is currently under study at COMMEDIA is the reconstruction of the flow state from Doppler ultrasound measurements. This is a cheap and largely available imaging modality where the measure can be interpreted as the average on a voxel of the velocity along the direction of the ultrasound beam. The goal is to perform a full-state estimation in a time compatible with a realistic application.

A second problem which is relevant is the flow and wall dynamics reconstruction using 4D-flow MRI. This imaging modality is richer than Doppler ultrasound and provides directly a measure of the 3D velocity field in the voxels. This enables the use of direct estimation methods at a reduced computational cost with respect to the traditional variational data assimilation approaches. Yet, the sensitivity of the results to subsampling and noise is still not well understood.

We also propose to address the issues related to uncertainty quantification. Indeed, measurements are corrupted by noise and the parameters as well as the available data of the system are either hidden or not known exactly (see [59]). This uncertainty makes the estimation difficult and has a large impact on the precision of the reconstruction, to be quantified in order to provide a reliable tool.

3.2.2 Safety pharmacology

One of the the most important problems in pharmacology is cardio-toxicity (see [58]). The objective is to predict whether or not a molecule alters in a significant way the normal functioning of the cardiac cells. This problem can be formulated as inferring the impact of a drug on the ionic currents of each cell based on the measured electrical signal (e.g., electrograms from Micro-Electrodes Arrays). The proposed approach in collaboration with two industrial partners (NOTOCORD and Ncardia) consists in combining available realistic data with virtual ones obtained by numerical simulations. These two datasets can be used to construct efficient classifiers and regressors using machine learning tools (see [42]) and hence providing a rapid way to estimate the impact of a molecule on the electrical activity. The methodological aspects of this work are addressed in Section 3.3.3.

3.3 Methodological core

The work described in this section is aimed at investigating fundamental mathematical and numerical problems which arise in the first two research axes.

3.3.1 Mathematical analysis of PDEs

The mathematical analysis of the multi-scale and multi-physics models are a fundamental tool of the simulation chain. Indeed, well-posedness results provide precious insights on the properties of solutions of the systems which can, for instance, guide the design of the numerical methods or help to discriminate between different modeling options.

Fluid-structure interaction. Most of the existing results concern the existence of solutions locally in time or away from contacts. One fundamental problem, related to the modeling and simulation of valve dynamics (see Sections 3.1.1 and 3.3.2), is the question of whether or not the model allows for contact (see [57, 55]). The proposed research activity is aimed at investigating the case of both immersed rigid or elastic structures and explore if the considered model allows for contact and if existence can be proved beyond contact. The question of the choice of the model is crucial and considering different types of fluid

(Newtonian or non-Newtonian), structure (smooth or rough, elastic, viscoelastic, poro-elastic), or various interface conditions has an influence on whether the model allows contact or not.

Fluid–structure mixture. The main motivation to study fluid-solid mixtures (i.e., porous media consisting of a skeleton and connecting pores filled with fluid) comes from the modeling of the lung parenchyma and cerebral hemorrhages (see Sections 3.1.1–3.1.2). The Biot model is the most widely used in the literature for the modeling of poro-elastic effects in the arterial wall. Here, we propose to investigate the recent model proposed by the M3DISIM project-team in [47], which allows for nonlinear constitutive behaviors and viscous effects, both in the fluid and the solid. Among the questions which will be addressed, some of them in collaboration with M3DISIM, we mention the justification of the model (or its linearized version) by means of homogenization techniques and its well-posedness.

Fluid–particle interaction. Mathematical analysis studies on the Navier-Stokes-Vlasov system for fluid-particle interaction in aerosols can be found in [39, 41]. We propose to extend these studies to more realistic models which take into account, for instance, changes in the volume of the particles due to humidity.

3.3.2 Numerical methods for multi-physics problems

In this section we describe the main research directions that we propose to explore as regards the numerical approximation of multi-physics problems.

Fluid-structure interaction. The spatial discretization of fluid-structure interaction (FSI) problems generally depends on the amount of solid displacement within the fluid. Problems featuring moderate interface displacements can be successfully simulated using (moving) fitted meshes with an arbitrary Lagrangian-Eulerian (ALE) description of the fluid. This facilitates, in particular, the accurate discretization of the interface conditions. Nevertheless, for problems involving large structural deflections, with solids that might come into contact or that might break up, the ALE formalism becomes cumbersome. A preferred approach in this case is to combine a Eulerian formalism in the fluid with an unfitted mesh discretization, in which the fluid-structure interface deforms independently of a background fluid mesh. In general, traditional unfitted mesh approaches (such as the immersed boundary and the fictitious domain methods [67, 38, 54, 36]) are known to be inaccurate in space. These difficulties have been recently circumvented by a Nitsche-based cut-FEM methodology (see [33, 43]). The superior accuracy properties of cut-FEM approaches comes at a price: these methods demand a much more involved computer implementation and require a specific evaluation of the interface intersections.

As regards the time discretization, significant advances have been achieved over the last decade in the development and the analysis of time-splitting schemes that avoid strong coupling (fully implicit treatment of the interface coupling), without compromising stability and accuracy. In the vast majority of these studies, the spatial discretization is based on body fitted fluid meshes and the problem of accuracy remains practically open for the coupling with thick-walled structures (see, e.g., [52]). Within the unfitted mesh framework, splitting schemes which avoid strong coupling are much more rare in the literature.

Computational efficiency is a major bottleneck in the numerical simulation of fluid-structure interaction problems with unfitted meshes. The proposed research activity is aimed at addressing these issues. Another fundamental problem that we propose to face is the case of topology changes in the fluid, due to contact or fracture of immersed solids. This challenging problem (fluid-structure-contact-fracture interaction) has major role in many applications (e.g., heart valves repair or replacement, break-up of drug-loaded micro-capsules) but most of the available studies are still merely illustrative. Indeed, besides the numerical issues discussed above, the stability and the accuracy properties of the numerical approximations in such a singular setting are not known.

Fluid–particle interaction and gas diffusion. Aerosols can be described through mesoscopic equations of kinetic type, which provide a trade-off between model complexity and accuracy. The strongly coupled fluid-particle system involves the incompressible Navier-Stokes equations and the Vlasov equation. The proposed research activity is aimed at investigating the theoretical stability of time-splitting schemes for this system. We also propose to extend these studies to more complex models that take into account the radius growth of the particles due to humidity, and for which stable, accurate and mass conservative schemes have to be developed.

As regards gas diffusion, the mathematical models are generally highly non-linear (see, e.g., [64, 66, 40]). Numerical difficulties arise from these strong non linearities and we propose to develop numerical schemes able to deal with the stiff geometrical terms and that guarantee mass conservation. Moreover, numerical diffusion must be limited in order to correctly capture the time scales and the cross-diffusion effects.

3.3.3 Statistical learning and mathematical modeling interactions

Machine learning and in general statistical learning methods (currently intensively developed and used, see [34]) build a relationship between the system observations and the predictions of the QoI (quantities of interest) based on the *a posteriori* knowledge of a large amount of data. When dealing with biomedical applications, the available observations are signals (think for instance to images or electro-cardiograms, pressure and Doppler measurements). These data are high dimensional and the number of available individuals to set up precise classification/regression tools could be prohibitively large. To overcome this major problem and still try to exploit the advantages of statistical learning approaches, we try to add, to the a posteriori knowledge of the available data an *a priori* knowledge, based on the mathematical modeling of the system. A large number of numerical simulations is performed in order to explore a set of meaningful scenarios, potentially missing in the dataset. This *in silico* database of virtual experiments is added to the real dataset: the number of individuals is increased and, moreover, this larger dataset can be used to compute semi-empirical functions to reduce the dimension of the observed signals.

Several investigations have to be carried out to systematically set up this framework. First, often there is not a single mathematical model describing a physiological phenomenon, but hierarchies of models of different complexity. Every model is characterized by a model error. How can this be accounted for? Moreover, several statistical estimators can be set up and eventually combined together in order to improve the estimations (see [61]). Other issues have an actual impact and has to be investigated: what is the optimal number of *in silico* experiments to be added? What are the most relevant scenarios to be simulated in relation to the statistical learning approach considered in order to obtain reliable results? In order to answer to these questions, discussions and collaborations with statistics and machine learning groups have to be developed.

3.3.4 Tensor approximation and HPC

Tensor methods have a recent significant development because of their pertinence in providing a compact representation of large, high-dimensional data. Their applications range from applied mathematics and numerical analysis to machine learning and computational physics. Several tensor decompositions and methods are currently available (see [56]). Contrary to matrices, for tensors of order higher or equal to three, there does not exist, in general, a best low rank approximation, the problem being ill posed (see [69]). Two main points will be addressed: (i) The tensor construction and the multi-linear algebra operations involved when solving high-dimensional problems are still sequential in most of the cases. The objective is to design efficient parallel methods for tensor construction and computations; (ii) When solving high-dimensional problems, the tensor is not assigned; instead, it is specified through a set of equations and tensor data. Our goal is to devise numerical methods able to (dynamically) adapt the rank and the discretization (possibly even the tensor format) to respect the chosen error criterion. This could, in turn, improve the efficiency and reduce the computational burden.

These sought improvements could make the definition of parsimonious discretizations for kinetic theory and uncertainty quantification problems (see Section 3.2.1) more efficient and suitable for a HPC paradigm. This work will be carried out in collaboration with Olga Mula (TU Eindhoven) and MATHERIALS project-teams.

4 Application domains

4.1 Cardiovascular hemodynamics

The heart is a double pump whose purpose is to deliver blood to the tissue and organs of the body. This function is made possible through the opening and closing of the heart valves. Cardiac diseases generally manifest by affecting the pumping function of the heart. Numerical simulations of cardiac hemodynamics, in normal and pathological conditions, are recognized as a tool of paramount importance for improving the understanding, diagnosis and treatment of cardiac pathologies, and also for the development of implantable devices (see, e.g., [65, 46]). As an example, we can mention the case of cardiac mitral valve regurgitation, one of the most common heart valve diseases. For this pathology, clinical data are known to be insufficient for determining the optimal timing for surgery, the best surgical strategy and the long-term outcome of a surgical repair. Contrary to imaging techniques, numerical simulations provide local information, such as pressure and stresses, which are of fundamental importance for the prediction of the mechanical behavior of native valves and of implantable devices.

4.2 Respiratory flows

Respiration involves the transport of air through the airways from the mouth to the alveoli of the lungs. These units where diffusion of oxygen and carbon dioxide takes place, are surrounded by a viscoelastic medium (the parenchyma) consisting of blood vessels and collagen fibers. Air flows due to the displacement of the diaphragm, which drives the pulmonary parenchyma. Accidental inhalations of foreign bodies or pathologies such as asthma, emphysema and fibrosis might prevent the lung of fulfilling its function. Therapies mostly use aerosols (set of small particles, solid or liquid), which must reach the specific areas of the lung targeted for treatment. Understanding the airflow mechanisms within the respiratory network is a fundamental ingredient for predicting the particles motion and their deposition (see, e.g., [44]). Moreover, understanding of the gas diffusion in the lung is also of major importance since the main function of this organ is to deliver oxygen to the blood.

4.3 Safety pharmacology

The problem of safety pharmacology can be summarized as follows: given a molecule which is a candidate to become a drug, is its use dangerous due to side effects? Among all the different problems to be addressed, one of the most relevant questions in pharmacology is cardio-toxicity (see [58]). More precisely, the objective is to determine whether or not a molecule alters in a significant way the normal functioning of the cardiac cells. To answer these questions, the CiPA initiative promotes the introduction of novel techniques and their standardisation (see [50]). One of the proposed tests of the CiPA panel is to measure the electrical activity using Micro-Electrodes Array: these are microchips that record the electrical activity of an ensemble of cells. The task is to infer the impact of a drug on the ionic currents of each cell based on the electrical signal measured (electrograms) and, in perspective, to be able to assess whether a molecule can induce arrhythmia (see [49]).

5 Latest software developments, platforms, open data

5.1 Latest software developments

5.1.1 FELiScE

Name: Finite Elements for Life SCiences and Engineering problems

Keywords: Finite element modelling, Cardiac Electrophysiology, Cardiovascular and respiratory systems

Functional Description: FELiScE is a finite element developed by COMMEDIA project-team. One specific objective of this code is to provide in a unified software environment all the state-of-the-art tools needed to perform simulations of the complex respiratory and cardiovascular models considered in the two teams – namely involving fluid and solid mechanics, electrophysiology, and the various associated coupling phenomena. FELISCE is written in C++ and open source, and may be later released as an opensource library. FELiScE was registered in July 2014 at the Agence pour la Protection des Programmes under the Inter Deposit Digital Number IDDN.FR.001.350015.000.S.P.2014.000.10000.

URL: https://team.inria.fr/commedia/software/felisce/

Contact: Miguel Angel Fernandez Varela

Participants: Romain Lemore, Marguerite Champion, Daniele Carlo Corti, Miguel Angel Fernandez Varela, Marina Vidrascu, Oscar Ruz, Carlos Brito Pacheco

5.1.2 FELiScE-NS

Keywords: Thin-walled solids, Incompressible flows

Functional Description: FELiScE-NS is a set of finite elements solvers for incompressible fluids (fractional-step schemes) and non-linear thin-walled structures (3D shells, and 2D curved beams) developed in the framework of the FELiScE library. FELiSCe-NS was registered in 2018 at the Agence pour la Protection des Programmes Inter Deposit Digital Number IDDN.FR.001.270015.000.S.A.2018.000.31200.

Contact: Miguel Angel Fernandez Varela

Participants: Oscar Ruz, Miguel Angel Fernandez Varela, Marina Vidrascu, Daniele Carlo Corti

5.1.3 ADAPT

Name: Adaptive Dynamical Approximation via Parallel Tensor methods

Keywords: Scientific computing, Tensor decomposition, Partial differential equation

Functional Description: ADAPT is a library containing methods for scientific computing based on tensors. In many fields of science and engineering we need to approximate the solution of high-dimensional problems. In this library we propose a collection of methods to parsimoniously discretise high-dimensional problems. These methods are mainly based on tensors.

Contact: Damiano Lombardi

Participants: Virginie Galland, Damiano Lombardi, Sebastien Riffaud

6 New results

6.1 Cardiovascular hemodynamics

Participants: Miguel Angel Fernández Varela, Oscar Ruz, Marina Vidrascu.

The thin-walled nature of the atrial wall can lead to numerical locking issues when using 3D models discretized with standard finite elements. In order to circumvent these issues, in [23] we introduce a comprehensive electromechanical model of the left atrium based on a 3D-shell formulation. The model integrates both the passive and active components of the atrial tissue, while blood flow and the mitral valve dynamics are described in a lumped parameter fashion. The resulting model is discretized with a finite element approach specifically designed to mitigate numerical locking. The effectiveness of the proposed approach is evaluated by comparing the numerical results with biomarkers reported in the literature, in the case of both healthy and pathological conditions.

6.2 Respiratory flows

Participants: Céline Grandmont, Frédèrique Noël.

In [21] we propose a new nonlinear coupled 1D model to describe lung ventilation and the transport and diffusion of both oxygen and carbon dioxide in the bronchial tree through the blood. It takes into account the so called Bohr-Haldane effect and is driven by the applied pleural pressure. The ability of this model to recover standard acknowledged values in healthy situations is provided. One key aspect is that, contrary to its 0D counterpart, it naturally takes into account mixing of gases along the tree and a time delay as the gases have to be transported before reaching the alveoli. We further investigate the sensitivity of both the 1D model and its 0D counterpart with respect to the breathing pattern by considering two types of pleural applied pressure: a piecewise constant one and a piecewise exponential one for various values of the breathing period, inspiratory ratio and pressure amplitude. We finally explore which cost functions the observed stereotypical breathing scenario may optimize, underlying the fact that it should be a combination of several criteria: low effort and small lung distension while maintaining carbon dioxide arterial partial pressure at a given level.

6.3 Simulation with data interaction

Participants: Miguel Angel Fernández Varela, Gaël Le Ruz, Damiano Lombardi, Fabien Vergnet, Marina Vidrascu.

In [32] we propose a mathematical model of the photoplethysmography (PPG) measurements. This consists in flashing light on a tissue and measuring the amount of light which comes back. As the tissue evolves, the signal changes in time. The goal of the work consists in going beyond this rough intuitive explanation and providing a more quantitative understanding of this measurement process. We propose a poro-elastic model for the biological tissue coupled with a diffusion approximation of the radiative transport equation in order to describe the light. The model is discretised by means of low-order finite elements. A first validation against real data showed that the model is able to provide an interpretation of the measurement process and that it is possible to estimate haemodynamics quantities (such as flow or relative pressure) based on the PPG signal.

In [28] we revisit the direct method for the reconstruction of coefficients in second order elliptic partial differential equations. Two model problems are considered: first the reconstruction of the diffusion coefficient in a scalar elliptic problem and second the reconstruction of the shear modulus in the elastography problem. To highlight the versatility of the framework, different notions of stability are exploited in the two situations. In the scalar case, the system is interpreted as a hyperbolic transport equation and an inf-sup condition on the discrete level is leveraged for the analysis of the numerical method. We obtain error estimates on the reconstruction coefficient that are suboptimal by half an order, which is known to be sharp on general meshes. In the vector case, the minimization of the residual in dual norm and a stability result on the continuous problem lead to error estimates that are optimal compared to the approximation. For both problems, the theoretical results are illustrated by some numerical examples.

In [31], we adopt an optimal control viewpoint to formulate a rigorous deterministic filtering theory when the dynamics and the observations are defined on manifolds. Therefore, our result extends the Mortensen observer to closed manifolds, namely a compact manifold without boundary, in both continuous and discrete time, where the second ultimately yields a convergent time discretization of the first. The resulting observer requires the computation of the viscosity solution of a Hamilton-Jacobi-Bellman equation on the state manifold, which we illustrate on the sphere.

In [30] we propose a numerical method to approximate the *log* operation on a Riemannian manifold as well as the Hessian of the squared distance. First, we write the boundary value problem of the geodesics as the minimisation of the geodesic energy with fixed endpoints, and write the weak formulation of the Euler-Lagrange equations. We introduce a fixed-point at continuous level, for which, under certain geometrical assumptions, we can prove that the iterations are well posed and convergent. When the fixed-point iterations are discretised by means of the finite element methods, the discrete iterations inherits the properties of the continuous ones. Moreover, by considering the sensitivity equations of the Euler-Lagrange equations we can write a system of $d + 1$ equations (where d is the manifold dimension) making it possible to estimate the Hessian of the squared distance. Some numerical tests on the sphere show that the proposed numerical method converges at the expected order.

6.4 Numerical methods for multi-physics problems

Participants: Miguel Angel Fernández Varela.

In [29] we consider a loosely coupled, non-iterative Robin-Robin coupling method proposed and analyzed in [Numer. Algorithms, 99:921-948, 2025] for a parabolic-parabolic interface problem. We modify the first step of the scheme so that several error difference quantities remain higher order convergence without requiring additional assumptions. Numerical results are presented to support our findings.

6.5 Tensor approximation and HPC

Participants: Damiano Lombardi.

In [27] we propose a numerical method to solve large scale matrix equations. In particular, we focus on the matrix equations which arise after space semi-discretisation of non-linear problems (going beyond the case of parametric PDEs). The method leverages the CUR matrix decomposition and Krylov iteration in order to estimate a low-rank decomposition of the solution of the matrix equation. The problem being highly non-linear, we introduce a fixed point. Given the current solution, by exploiting an empirical interpolation method, we are able to select sets of rows and columns. Following the principle of cross approximation we make the residual vanish on the selected rows and columns: the resulting two sets of equations are solved by using a Krylov method, providing an updated solution. Several numerical test-cases make it possible to assess the behavious of the method and its performances.

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

CASIS

Participants: Miguel Ángel Fernández Varela *(coordinator)*, Damiano Lombardi, Romain Lemore.

Calibration of vascular fluid-structure interaction simulations from 4D-flow MRI data.

Dassault Systèmes

Participants: Abdelkhalak Chetoui, Miguel Ángel Fernández Varela, Damiano Lombardi *(coordinator)*.

Reduced order modelling and data assimilation for the haemodynamics of congenital heart diseases.

8 Partnerships and cooperations

8.1 International initiatives

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

DIAFLOP

Participants: Guillaume Delay, Davide Pietro Duva, Miguel Angel Fernández Varela, Corrie James, Romain Lemore.

Title: Data Integration and Assimilation for FLOw Problems

Duration: 2025-207

Coordinator: Miguel Angel Fernández Varela

Partners:

- University College London London, UK

Inria contact: Miguel Angel Fernández Varela

UCL contact: Erik Burman

Summary: The purpose of the DIAFLOP Associate Team is to exploit the complementary expertise of both research groups in mathematical analysis, numerical analysis, scientific computing and data assimilation in order to develop innovative forward and inverse techniques in the context of cardiovascular applications. The main scientific goal is to develop new efficient and accurate methods for the integration and assimilation of data in the numerical approximation of solutions to partial differential equations modeling blood flows. This includes both geometrical and kinematical data. A key aspect is the use of both individual and collective data.

8.2 International research visitors

8.2.1 Visits of international scientists

Other international visits to the team

Erik Burman

Status Professor

Institution of origin: UCL

Country: UK

Dates: March, October 2025 (2 weeks)

Context of the visit: Inria-UCL DIAFLOP Associate Team

Mobility program/type of mobility: research stay

Buyang Li

Status Professor

Institution of origin: The Hong Kong Polytechnic University

Country: Hong Kong

Dates: June-July 2025 (4 weeks)

Context of the visit: Inria Paris Invited Professors Program

Mobility program/type of mobility: research stay & lecture

Maxim Olshanskii

Status Professor

Institution of origin: Uniersity of Houston

Country: USA

Context of the visit: Research collaboration

Dates: June, July 2025 (1 week)

Mobility program/type of mobility: research stay & lecture

8.3 National initiatives

CoCop: Heart-Lung Coupling: aid to monitor cardio-respiratory functions in intensive care

Participants: Céline Grandmont, Frédérique Noël, Fabien Vergnet, Romain Lopez-Surjus.

Funding: Inria Exploratory Actions

Duration: 2024–2027

Coordinator: Céline Grandmont

Partners: ANANKE project-team (Dominique Chapelle, Philippe Moireau), APHP Lariboisière Hospital (Fabrice Vallée)

Summary: The project seeks to respond to the clinical need for a better understanding of cardio-respiratory functions for patients placed under mechanical ventilation. It aims in particular to propose ventilatory maneuvers or minimally invasive measurements that can be carried out at the bedside of patients, making it possible to estimate the condition of the lung, the level of blood perfusion and help optimize ventilator settings in order to minimize damage to the lungs.

MediTwin

Participants: Carlos Brito Pacheco, Abdelkhalak Chetoui, Miguel Angel Fernández Varela, Damiano Lombardi, Marina Vidrascu.

Funding: Bpifrance

Duration: 2024-2029

Local coordinator: Miguel Angel Fernández Varela

Partners: Dassault Systèmes

Summary: Reduced and 3D modeling and simulation of cardiac hemodynamics, notably of patohological scenarios such as the Hypoplastic Left Heart Syndrome (HLHS), whith the purpose of assesing different surgicals options.

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Scientific events: organisation

- Guillaume Delay
  - Co-organizer of the Scientific Computing Seminar, joint event between Inria Paris and Laboratoire Jacques-Louis Lions
  - Co-organizer of the Cemracs Summer School (July-August 2025): web page
- Miguel Angel Fernández Varela
  - Co-organiser of the Joint Brazil-Chile-Inria MS on Innovative Numerical Methods for Fluids, 23rd IACM Computational Fluids Conference, Santiago de Chile, Chile, March 2025
  - Co-organiser of the DIAFLOP Inria-UCL Asociated Team Kick-off meeting, London, UK, December 2025

- Damiano Lombardi
  - Co-organizer of the Scientific Computing Seminar, joint event between Inria Paris and Laboratoire Jacques-Louis Lions

Member of the conference program committees

- Migue Angel Fernández Varela
  - Member of the FIMH 2025 Program Committee

9.1.2 Journal

Member of the editorial boards

- Céline Grandmont
  - Mathematical Modelling of Natural Phenomena
  - Journal of Mathematical Fluid Mechanics
  - ESAIM: Mathematical Modelling and Numerical Analysis

9.1.3 Invited talks

- Marguerite Champion
  - Invited speaker, Modeling, Analysis and Simulation Working Group of MAP5 (Université Paris Cité), November 2025
- Guillaume Delay
  - Invited talk in mini-symposium ENUMATH 2025, Heidelberg, Germany, September 2025
- Miguel Angel Fernández Varela
  - Invited talk, Inria-LNCC-UDEC Workshop on Computational Fluids: Challenges and New Trends, Petrópolis, Brazil, March 2025
  - Invited talk, 23rd IACM Computational Fluids Conference, Santiago de Chile, Chile, March 2025
  - Invited talk at Inria-Brasil hybrid workshop on Digital Health, April 2025 (online)
  - Invited speaker, Numerical Analysis of Interface and Multiphysics Problems MATRIX research program, Creswick Campus of The University of Melbourne, Australia, May 2025
  - Invited talk, 20th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering (CMBBE 2025), Barcelona, Spain, September 2025
  - Seminar, CHRU of Tours, Tours, France, November 2025 (online)
  - Invited talk, Symposium on Stabilized and Cut Finite Element Methods – Celebrating Peter Hansbo, Institut Mittag-Leffler, Stockholm, Sweden, December 2025 (online)
- Céline Grandmont
  - Invited talk, Modeling in Applied Mechanics : A symposium to honour Patrick Le Tallec, Ecole Polytechnique, NovembeDecember 2025
  - Plenary conference, Forum des jeunes Mathématiciennes et Mathématiciens, Bordeaux, November 2025
  - Invited talk, Closure conference of the ARC-ULB projet, Spa, Belgium, December 2025
  - Invited talk, Lung Modelling workshop, October 2025
  - Invited talk, ENUMATH 2025, Heidelberg, September 2025

  - Invited talk, Workshop "Mathematical modeling in biology and medicine", Vienna, Jul. 2025
  - Seminar MMCS, Institut Camille Jordan, May 2025
  - Seminar LJLL, Sorbonne Université, May 2025
  - Seminar, ULB, Bruxelles, Belgium, April 2025
  - Invited talk, PDEs journey of Université de Lorraine, April 2025
- Corrie James
  - Talk in MS, Math 2 Product, Valencia, Spain, June 2025
  - Talk at the Journées Maths Bio Santé, Montpellier, France, November 2025
- Damiano Lombardi
  - Seminar, LISN (Université Paris Sud, CNRS), October 2025
  - Keynote talk, Joint meeting of Austrian and German mathematical societies, symposium on scientific computing, Linz, September 2025
  - Invited talk, Workshop on Accurate Reduced Order Models for Industrial Applications, Bidart, September 2025
- Frédérique Noël
  - Invited talk, Economic principles in Cell Biology Summer School, Vienna, Austria, July 2025 (online)
  - MS talk, International Conference on Computational Bioengineering (ICCB), Rome, Italy, September 2025
- Oscar Ruz
  - Talk at FIMH 2025 Conference, Dallas, USA, June 2025
- Fabien Vergnet
  - PDE Seminar Laboratoire de Mathématiques de Versailles, Versailles, France, March 2025
  - Rencontres Inria-LJLL in Scientific Computing, Inria Paris, Paris, France, March 2025

9.1.4 Research administration

- Céline Grandmont
  - Member of the Inria parity and equal opportunities committee (Coordinator of the working group on gender-based and sexual violence, presentations at the Inria project-team comittees of Inria Grenoble and Inria Lille)
  - Member of the LJLL and Inria parity and equal opportunities committees

9.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

- Licence:
  - Marguerite Champion
    - Numerical analysis, 48h, L3, Sorbonne Université
  - Davide Pietro Duva
    - Fourier analysis: L3, 12 hours, Polytech Sorbonne, Sorbonne Université
    - Mathematics for engineering: L3, 30 hours, Polytech Sorbonne, Sorbonne Université
  - Marguerite Champion

    * Numerical analysis, 24h, L3, Sorbonne Université
    * Python, 32h, L2, Sorbonne Université
  - Corrie James
    * Optimization, 45h, L3, Université de Versailles Saint-Quentin-en-Yvelines
  - Gaël Le Ruz
    * Linear algebra and ODE, 30h, L3, Polytech Sorbonne
    * Numerical Analysis for PDE, 12h, L3, Polytech Sorbonne
  - Fabien Vergnet
    * Numerical analysis and ODE, 66h, L3, Polytech Sorbonne
    * Fourier Analysis 23h, L3, Polytech Sorbonne
    * Mathematical tools for ingeneers, 18h, L3, Polytech Sorbonne

- Master:
  - Guillaume Delay
    * Preparation to Agrégation, 34h, M2, Sorbonne Université
    * Numerical analysis for PDE, 18h, M1, PolyTech Sorbonne
  - Miguel Angel Fernández Varela
    * Mathematical models and numerical methods for hemodynamics simulations, 20h, M2, Sorbonne Université
  - Céline Grandmont
    * Hands-on sessions, PDEs Approximation, 46 h, M1, Sorbonne Université
  - Damiano Lombardi
    * Lecture, 1.5h, Modeling the electro-physiology of heart, NovembeDecember 2023, Ecole des Mines Paristech.
  - Frédérique Noël
    * Programming in C++, 36h, M1, Sorbonne Université
    * Numerical linear algebra, 18h, M1, Sorbonne Université

9.2.1 Supervision

- PhD defended on January 31, 2025: Oscar Ruz, Mathematical modeling and numerical simulation of left heart hemodynamics with fluid–structure interactions, [26]. Supervisors: Dominique Chapelle, Miguel Angel Fernández Varela & Marina Vidrascu

- PhD defended on September 25, 2025: Marguerite Champion, Modeling, analysis and simulation of fluid-structure-interaction with contact, [24]. Supervisors: Miguel Angel Fernández Varela, Céline Grandmont, Fabien Vergnet & Marina Vidrascu

- PhD defended on December 1, 2025: Gaël Le Ruz, Observer theory in general constrained spaces – from formulations to applications, [25]. Since October 2022. Supervisors: Damiano Lombardi & Philippe Moireau

- PhD in progress: Corrie James, Data-Modeling interaction for biomedical applications. Since October 2023. Supervisors: Muriel Boulakia & Damiano Lombardi

- PhD in progress: Romain Lemore, Modeling and patient specific fluid-structure interaction simulations of aortic pathological configurations. Since July 2024. Supervisors: Miguel Angel Fernández Varela & Damiano Lombardi

- PhD in progress: Romain Lopez-Surjus, Mathematical and numerical modelling of the cardio respiratory system. Since October 2024. Supervisors: Céline Grandmont, Frédérique Noël & Fabien Vergnet
- PhD in progress: Davide Pietro Duva, Divergence-free finite elements for direct and inverse problems. Since December 2024. Supervisors: Guillaume Delay & Miguel Angel Fernández Varela
- PhD in progress: Abdelkhalak Chetoui, Reduced order modelling and data assimilation for the haemodynamics of congenital heart diseases. Since April 2025. Damiano Lombardi, Miguel Angel Fernández Varela & Hernán Morales
- Internship: Dongjiao Hong. Supervisors: Damiano Lombardi & Marina Vidrascu
- Internship: Renee Crispo. Supervisor: Miguel Angel Fernández Varela

9.2.2 Juries

- Damiano Lombardi
  - Co-president of CES (Commission Emploi Scientifique), Inria Paris
  - Participation to the SMAI-GAMNI prize selection committee

9.3 Popularization

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

- Daniele Carlo Corti, Miguel Angel Fernández Varela
  - Popularization video on the numerical simulation of the heart: youtube video

9.3.2 Participation in Live events

- Marguerite Champion
  - Participation in a FIRST event aimed at encouraging female high-school students to pursue scientific studies, Lycée Pierre-Gilles de Gennes (Paris 13), February 2025
- Céline Grandmont
  - Two Interventions at the SMAI & Musée des arts et métiers Cycle: youtube link
  - Chiche intervention, Emilie du Chatelet Highschool, spring 2025
  - Participation to "Maths C pour Elle week", June 2025

10 Scientific production

10.1 Major publications

[1] M. Barré, C. Grandmont and P. Moireau. ‘Analysis of a linearized poromechanics model for incompressible and nearly incompressible materials’. In: *Evolution Equations and Control Theory* (2022). URL: https://hal.inria.fr/hal-03501526.

[2] L. Boudin, C. Grandmont, B. Grec and S. Martin. ‘A coupled model for the dynamics of gas exchanges in the human lung with Haldane and Bohr’s effects’. In: *Journal of Theoretical Biology* 573 (2023), p. 111590. DOI: 10.1016/j.jtbi.2023.111590. URL: https://hal.science/hal-03883301.

[3] L. Boudin, C. Grandmont, B. Grec, S. Martin, A. Mecherbet and F. Noël. ‘Fluid-kinetic modelling for respiratory aerosols with variable size and temperature’. In: *ESAIM: Proceedings and Surveys* 67 (2020), pp. 100–119. DOI: 10.1051/proc/202067007. URL: https://hal.archives-ouvertes.fr/hal-02092574.

[4] M. Boulakia, E. Burman, M. A. Fernández and C. Voisembert. 'Data assimilation finite element method for the linearized Navier-Stokes equations in the low Reynolds regime'. In: *Inverse Problems* 36.8 (1st May 2020). DOI: 10.1088/1361-6420/ab9161. URL: https://hal.inria.fr/hal-02318504.

[5] E. Burman, R. Durst, M. A. Fernández, J. Guzmán and O. Ruz. 'Robin-Robin loose coupling for incompressible fluid-structure interaction: non-linear setting and nearly-optimal error analysis'. In: *Journal of Scientific Computing* 104.34 (5th May 2025). DOI: 10.1007/s10915-025-02939-5. URL: https://inria.hal.science/hal-04258861.

[6] M. Champion, M. A. Fernández, C. Grandmont, F. Vergnet and M. Vidrascu. 'On the analysis of a mechanically consistent model of fluid-structure-contact interaction'. In: *Mathematics in Engineering* 6.3 (2024), pp. 425–467. DOI: 10.3934/mine.2024018. URL: https://hal.science/hal-04229012.

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[8] V. Ehrlacher, M. Fuente-Ruiz and D. Lombardi. 'SoTT: greedy approximation of a tensor as a sum of Tensor Trains'. In: *SIAM Journal on Scientific Computing* 44.2 (21st Mar. 2022). DOI: 10.1137/20M1381472. URL: https://inria.hal.science/hal-03018646.

[9] F. Galarce, J.-F. Gerbeau, D. Lombardi and O. Mula. 'Fast reconstruction of 3D blood flows from Doppler ultrasound images and reduced models'. In: *Computer Methods in Applied Mechanics and Engineering* (1st Mar. 2021). DOI: 10.1016/j.cma.2020.113559. URL: https://hal.archives-ouvertes.fr/hal-02403686.

[10] C. Grandmont, C. Karamaoun, S. Martin and F. Noël. 'Sensitivity and optimality analysis of breathing scenarios for 1D or 0D models of gas diffusion in the lung'. In: *Journal of Theoretical Biology* 615 (7th Dec. 2025). URL: https://hal.science/hal-05019689.

[11] C. Grandmont and F. Vergnet. 'Existence and uniqueness for a quasi-static interaction problem between a viscous fluid and an active structure'. In: *Journal of Mathematical Fluid Mechanics* 23.45 (27th Mar. 2021). DOI: 10.1007/s00021-020-00552-0. URL: https://hal.archives-ouvertes.fr/hal-02493384.

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10.2 Publications of the year

International journals

[17] M. Boulakia, C. James and D. Lombardi. 'Numerical approximation of the unique continuation problem enriched by a database for the Stokes equations'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 59.3 (27th May 2025), pp. 1399–1435. DOI: 10.1051/m2an/2025024. URL: https://inria.hal.science/hal-04721560.

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[19] E. Burman, R. Durst, M. A. Fernández, J. Guzmán and O. Ruz. 'Robin-Robin loose coupling for incompressible fluid-structure interaction: non-linear setting and nearly-optimal error analysis'. In: *Journal of Scientific Computing* 104.34 (5th May 2025). DOI: 10.1007/s10915-025-02939-5. URL: https://inria.hal.science/hal-04258861.

[20] S. C. Faya, C. Wesley, M. Vidrascu, M. A. Fernández, P.-J. Guns and D. Lombardi. 'Validation of a mathematical model of arterial wall mechanics with drug induced vasoconstriction against ex vivo measurements'. In: *Cardiovascular Engineering and Technology* (1st July 2025). DOI: 10.1007/s13239-025-00796-9. URL: https://inria.hal.science/hal-04597238.

[21] C. Grandmont, C. Karamaoun, S. Martin and F. Noël. 'Sensitivity and optimality analysis of breathing scenarios for 1D or 0D models of gas diffusion in the lung'. In: *Journal of Theoretical Biology* 615 (7th Dec. 2025). URL: https://hal.science/hal-05019689 (cit. on p. 12).

[22] O. Ruz, J. Diaz, M. Vidrascu, P. Moireau, D. Chapelle and M. A. Fernández. 'Left heart hemodynamics simulations with fluid-structure interaction and reduced valve modeling'. In: *International Journal for Numerical Methods in Biomedical Engineering* 41.9 (10th Aug. 2025), e70088. DOI: 10.1002/cnm.70088. URL: https://hal.science/hal-04733426.

Edition (books, proceedings, special issue of a journal)

[23] *3D-Shell Electromechanical Modeling of the Left Atrium*. Functional Imaging and Modeling of the Heart. Vol. 15672. Dallas (TX), United States: Springer, June 2025. DOI: 10.1007/978-3-031-94559-5_5. URL: https://inria.hal.science/hal-05044627 (cit. on p. 12).

Doctoral dissertations and habilitation theses

[24] M. Champion. 'Modelling, analysis and simulation of fluid-structure interaction with contact'. Sorbonne Université, 25th Sept. 2025. URL: https://theses.hal.science/tel-05469998 (cit. on p. 19).

[25] G. Le Ruz. 'Optimal observer theory in manifolds – from formulations to applications'. Sorbonne université, 1st Dec. 2025. URL: https://inria.hal.science/tel-05429233 (cit. on p. 19).

[26] O. Ruz Núñez. 'Mathematical modeling and numerical simulation of left heart hemodynamics with fluid-structure interaction'. Sorbonne Université, 31st Jan. 2025. URL: https://theses.hal.science/tel-04973025 (cit. on p. 19).

Reports & preprints

[27] S. Akbari, D. Lombardi and H. Babaee. *A CUR Krylov Solver for Large-Scale Linear Matrix Equations*. Nov. 2025. URL: https://inria.hal.science/hal-05347946 (cit. on p. 14).

[28] M. Boulakia, E. Burman and M. A. Fernández. *Primal-dual finite element methods for the direct reconstruction of material coefficients in stationary elliptic problems*. 24th Oct. 2025. URL: https://hal.science/hal-05330332 (cit. on p. 13).

[29] E. Burman, M. A. Fernández, J. Guzmán and S. Liu. *An improved Robin-Robin coupling method for parabolic-parabolic interface problems*. 9th Sept. 2025. URL: https://inria.hal.science/hal-05290627 (cit. on p. 14).

[30] G. Le Ruz and D. Lombardi. *Finite elements approximation of the boundary value problems of geodesics*. 7th Nov. 2025. URL: https://inria.hal.science/hal-05354459 (cit. on p. 13).

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[33] F. Alauzet, B. Fabrèges, M. A. Fernández and M. Landajuela. 'Nitsche-XFEM for the coupling of an incompressible fluid with immersed thin-walled structures'. In: *Comput. Methods Appl. Mech. Engrg.* 301 (2016), pp. 300–335 (cit. on p. 9).

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[42] L. Breiman. *Classification and regression trees*. Routledge, 2017 (cit. on p. 8).

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