

Evaluation of Inria theme Distributed programming and Software engineering

Project-team DIVERSE

<https://www.diverse-team.fr>

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Project-Team Title: Diversity-centric Software Engineering DIVERSE

Theme: Distributed programming and Software engineering

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Research Center: Rennes – Bretagne Atlantique

Common Project-Team with: University of Rennes 1, CNRS, INSA Rennes

DIVERSE is located on Beaulieu campuses: Rennes

A web version of this report is available at <https://www.diverse-team.fr/reporteval2021-40p/>

Abstract:	iii	2.4.4 Software Language Ap- plications	9
1 Personnel	1	2.4.5 Collaborations	10
2 Research Goals and Results	4	2.4.6 External support	10
2.1 Keywords	4	2.4.7 Self Assessment	10
2.2 Context and Overall Goals of the Project	4	2.5 Research Axis 2: Variability modeling	11
2.3 Research axis	5	2.5.1 Personnel	11
2.4 Research Axis 1: Software Lan- guage Engineering	5	2.5.2 Project-Team Positioning Challenges	11
2.4.1 Personnel	5	Scientific objectives	11
2.4.2 Project-Team Positioning Challenges	6	2.5.3 Scientific Achievements	12
Scientific objectives	6	Modeling variability.	12
2.4.3 Scientific Achievements	7	Reverse engineering vari- ability.	12
Software Language Foundations	7	Testing and sampling variability.	13
Software Language de- velopment ap- proaches and IDEs	8	Learning variability.	14
		Teaching variability.	15
		2.5.4 Collaborations	15
		2.5.5 External support	15
		2.5.6 Self Assessment	15

2.6	Research Axis 3: Runtime configuration and deployment for software-defined network services	16	3.5	General Audience Actions	28
2.6.1	Personnel	16	3.6	Visibility	28
2.6.2	Project-Team Positioning Challenges	16	3.6.1	Awards	28
	Scientific objectives	16	3.6.2	Tutorials and Invited Conferences	29
2.6.3	Scientific Achievements	17	3.6.3	Program Committees, Editorial Boards, Conference Organization and Research Expertise	30
2.6.4	Collaborations	19	3.7	International Collaborations	30
2.6.5	External support	19		Inria Associated Teams and Other Formal Collaborations	30
2.6.6	Self Assessment	19		Informal Collaborations	31
2.7	Research Axis 4: Software implementation diversification	20		Visits of International Scientists	31
2.7.1	Personnel	20		Visits to International Teams	32
2.7.2	Project-Team Positioning Challenges	20	4	Funding	33
	Scientific objectives	20	5	Objectives for the Next Four Years	36
2.7.3	Scientific Achievements	21	5.1	Axis #1: Software Language Engineering	36
	Proactive program diversification.	21		Overall objective.	36
	Software evolution	21		DSL Executability.	37
	Multi-tier software diversification.	21		Modular & Distributed IDE.	37
2.7.4	Collaborations	22		Design Lab.	37
2.7.5	External support	22		Live & Polyglot Development.	38
2.7.6	Self Assessment	22		Self-Adaptable Language.	38
2.8	Evolution of Research Directions During the Evaluation Period	23	5.2	Axis #2: Spatio-temporal Variability in Software and Systems	38
3	Knowledge Dissemination	24		Overall objective.	38
3.1	Publications	24		Deep Software Variability.	38
	Publications in Main Journals:	24		Continuous Software Evolution.	39
	Publications in Major Conferences:	24	5.3	Axis #3: DevSecOps and Resilience Engineering for Software and Systems	39
	Selection of Publications	25		Overall objective.	39
3.2	Software	25		Secure & Resilient Architecture.	39
3.2.1	FAMILIAR	25		Smart CI/CD.	39
3.2.2	GEMOC Studio	25		Secure Supply Chain.	40
3.2.3	Descartes	26	6	Bibliography of the Project-Team	41
3.2.4	Kevoree	26			
3.2.5	amiunique	26			
3.2.6	Overall evaluation	27			
3.3	Technology Transfer and Socio-Economic Impact	27			
3.4	Teaching	27			
	Responsibilities:	28			
	Commitment in Summer Schools:	28			

Abstract: DiverSE’s research agenda is in the area of software engineering. In this broad domain we develop models, methodologies and theories to address the challenges raised by the emergence of several forms of diversity in the design, deployment and evolution of software intensive systems. The emergence of software diversity is an essential phenomenon in all application domains that we investigate with our industrial partners. These application domains range from complex systems such as systems of systems and Instrumentation and Control to pervasive combinations of Internet of Things and Internet of Services. Even if today these systems are apparently radically different, we envision a strong convergence of the scientific principles underpinning their construction and validation towards flexible and open yet dependable systems. In particular, we see that the required flexibility and openness raise challenges for the software layer of these systems that must deal with four dimension of diversity: the diversity of languages used by the stakeholders involved in the construction of these systems; the diversity of features (aka variability) required by the different customers; the diversity of runtime environments in which software has to run and adapt; the diversity of implementations that are necessary for resilience through redundancy.

In this context, the major software engineering challenge consists in handling diversity from variability in requirements and design to heterogeneous and dynamic execution environments. In particular, this requires considering that the software system must adapt, in unpredictable ways, to changes in the requirements and environment. Conversely, explicitly handling of diversity is a great opportunity to allow software to spontaneously explore alternative design solutions. Concretely, we want to provide software engineers with the ability:

- to characterize an “*envelope*” of possible variations
- to compose “envelopes” (to discover new macro envelopes in an opportunistic manner)
- to dynamically synthesize software inside a given envelope

The major scientific objective that we must achieve to provide such mechanisms for software engineering is synthesized below:

DiverSE long-term ambition

Automatically compose and synthesize software diversity from design to runtime to address unpredictable evolutions of software intensive systems. Software product lines and associated variability modeling formalisms represent an essential aspect of software diversity, which we already explored in the past, and that represent a major foundation of DiverSE’s research agenda. However, DiverSE also exploits other foundations to handle new forms of diversity: type theory and models of computation for the composition of languages; distributed algorithms and pervasive computation to handle the diversity of execution platforms; functional and qualitative randomized transformations to synthesize diversity for robust systems.

1 Personnel

Current Composition of the Project-Team:

Research Scientists and Faculty Members:

- Mathieu Acher, Associate Professor, Univ de Rennes I
- Olivier Barais, Team leader, Full Professor, Univ de Rennes I
- Arnaud Blouin, Associate Professor, HDR, INSA Rennes
- Johann Bourcier, Associate Professor, HDR, Univ de Rennes I
- Stéphanie Challita, Associate Professor, Univ de Rennes I, *from Sept 2020*
- Benoit Combemale, Full Professor, Univ de Rennes I
- Jean-Marc Jezequel, Full Professor, Univ de Rennes I
- Djamel Eddine Khelladi, Full time Researcher, CR CNRS, *from January 2019*
- Noel Plouzeau, Associate Professor, Univ de Rennes I
- Olivier Zendra, Full time Researcher, CR INRIA, *from Oct 2020*

Research Engineers:

- Didier Vojtisek, Inria
- Romain Belafia, Univ de Rennes I
- Romain Lefeuvre, Univ de Rennes I
- Bruno Lebon, INRIA

Post-docs:

- Dorian Leroy, INRIA
- Xhevahire Tërnavà, Univ de Rennes I
- Elyes Cherfa, Univ de Rennes I

PhD Students:

- Luc Lesoil, Univ Rennes I
- Alif Akbar Pranata, Inria
- June Benvegnu Sallou, Univ de Rennes I
- Emmanuel Chebbi, Inria
- Antoine Cheron, FaberNovel, granted by CIFRE
- Fabien Coulon, Obeo, granted by CIFRE
- Pierre Jeanjean, Inria
- Gauthier Lyan, Keolis Rennes, granted by CIFRE
- Hugo Martin, Univ de Rennes I
- Anne Bumiller, Orange, granted by CIFRE
- Cassius De Oliveira Puodzius, Inria
- Gwendal Jouneaux, Univ de Rennes I
- Quentin Le Dilavrec, Univ de Rennes I
- Georges Aaron Randrianaina, Univ de Rennes I

Administrative Assistants:

- Sophie Maupile, CNRS

External Collaborators:

- Gurvan Le Guernic, DGA

Personnel at the Start of the Evaluation Period (October 2016)

	INRIA	CNRS	University	Other	Total
DR (1) / Professors			2		2
CR (2) / Associate professors	1		5		6
Permanent engineers	1				1
Temporary engineers	2	1	2		5
Post-docs	1		2		3
PhD Students	3	2	7	2	14
Total	8	4	17	2	31

(1) “Senior Research Scientist (Directeur de Recherche)”

(2) “Junior Research Scientist (Chargé de Recherche)”

Personnel at the Time of the Evaluation (October 2021)

	INRIA	CNRS	University	Other	Total
DR / Professors			3		3
CR / Associate professors	1	1	5		7
Permanent engineers	1				1
Temporary engineers	1		2		3
Post-docs	1		2		3
PhD Students	4		6	4	14
Total	8	1	18	4	31

Changes in the Scientific Staff

	INRIA	CNRS	University	Other	Total
DR / Professors			+1		+1
CR / Assistant Professors		+1			+1

Current Position of Former Project-Team Members

- Caroline Landry, Software Development Manager at MediaKind, Rennes France
- Juliana Alves Pereira, Univ de Rennes I
- Erwan Bousse, Associate Professor at University of Nantes, France
- Oscar Luis Vera Perez, Research Engineer at MediaKind, Rennes France
- Youssou Ndiaye: Security Engineer at Famoco, Rennes, France
- Ludovic Mouline, Software Engineer at SHARE NOW, Luxembourg, Luxembourg
- Manuel Leduc, Research Engineer at XWiki, Paris, France
- José Galindo, Professor at Univ de Sevilla, Seville, Spain
- David Méndez-Acuña, Software Engineer at Adobe, Paris, France
- Francisco Javier Acosta Padilla, Embedded Hardware and Software Engineering Manager at KUGU, Berlin, Germany
- Jacky Bourgeois, Assistant Professor, TU Delft, Delft, Netherlands
- Mohammed Boussaa, Software Engineer at ActiveEon, Paris, France
- Gwendal Le Moulec, Software Engineer at Sopra Steria, Rennes, France
- Kevin Corre, Research engineer at EXFO, Rennes, France
- Paul Temple, Postdoc at Université de Namur, Namur, Belgium
- Amine Benelallam, Senior Software Engineer at MathWorks, Nanterre, France
- Marcelino Rodriguez Cancio, Chief Technology Officer at Couture Technologies, Nashville, Tennessee, United States
- Johan Pelay, teacher at Université de Pau et des Pays de l’Adour, Pau, France

- Pierre Laperdrix, full time researcher at CNRS, Lille, France
- Jean-Emile Dartois, Research Engineer at Orange Labs, Rennes France
- Alexandre Rio, OKWind, Research Engineer at OkWind, Vitre France
- Thomas Degueule, full time researcher at CNRS, Bordeaux, France

Last INRIA Enlistments

No new INRIA researcher has been recruited for the team during the period. Olivier Zendra, head of the Tamis team, joined the team in October 2020. Benoit Baudry, head of the DiverSE team until Sept 2017, moved to KTH Stockholm.

Comments:

The field of software engineering is at the crossroads of many fields. In particular, the proximity with the domain of system, distributed systems but also the numerous implications in the domain of software security imposes to have within the team many skills both on the technological aspects (technology in constant evolution) and in the domain of execution platforms, programming language, modeling, machine learning, statistics (empirical evaluation).

Following the move of Benoit Baudry to KTH Stockholm, Olivier Barais led the team from September 2017. In September 2017, Benoit Combemale took a full-professor position at the University of Toulouse. Jean-Marc Jézéquel was dean of IRISA (CNRS laboratories 1000 employees). Our priority was to quickly consolidate the team of permanent staff in order to be able to correctly supervise the many doctoral students who were present. For family reasons, Benoit Combemale had the opportunity to come back on a half-delegation to INRIA in September 2018 and to come definitely back to Rennes on a faculty position in September 2020. Since September 2020, he has informally assumed a role as scientific co-supervisor of the team. If the team is renewed, we will propose to INRIA to formalize this role. Djamel Eddine Khelladi was recruited as a tenured CNRS Research Scientist in January 2019, then Stéphanie Challita, a PhD student of the INRIA Spirals team, was recruited in September 2020 as a UR1 Associate Professor. Finally Olivier Zendra joined the team in October 2020. Jean-Marc Jézéquel is no longer director of IRISA since January 2021. In summary, in addition to the classic movements of many non-permanent staff during the period, there were also many arrivals and the departure of the initial team leader. The consolidation in terms of permanent staff has been mainly ensured by the CNRS and the University for the moment. There is no doubt that INRIA wishes to support the team in this growth but as in many fields, international competition is important for the recruitment of young scientists in the field.



Figure 1: The DIVERSE Group: A Software Engineering Group

2 Research Goals and Results

2.1 Keywords

Software Engineering: empirical software engineering, software maintenance & evolution, software language, software testing, domain-specific language, Software Architecture & Design, Dynamic reconfiguration, Web, Object-oriented programming, component-based design, middleware, Privacy-enhancing technologies, Security of equipment and software, resource management

Application Domains: software engineering, software industry, software evolution & maintenance, sustainable development, resource management, Internet of things, information systems, embedded systems, sensor networks for smart buildings, privacy, user interface engineering

2.2 Context and Overall Goals of the Project

DiverSE’s research agenda targets core values of software engineering. In this fundamental domain we focus and develop models, methodologies and theories to address major challenges raised by the emergence of several forms of diversity in the design, deployment and evolution of software-intensive systems. Software diversity has emerged as an essential phenomenon in all application domains born by our industrial partners. These application domains range from complex systems brought by systems of systems (addressed in collaboration with Thales, Safran, CEA and DGA) and Instrumentation and Control (addressed with EDF) to pervasive combinations of Internet of Things and Internet of Services (addressed with TellU and Orange) and tactical information systems (addressed in collaboration with civil security). Today these systems seem to be radically all different, but we envision a strong convergence of the scientific principles that underpin their construction and validation, bringing forwards sane and reliable methods for the design of **flexible and open yet dependable systems**. Flexibility and openness are both critical and challenging software layer properties that must deal with the following four dimensions of diversity: **diversity of languages**, used by the stakeholders involved in the construction of these systems; **diversity of features**, required by the different customers; **diversity of runtime environments**, in which software has to run and adapt; **diversity of implementations**, which are necessary for resilience by redundancy.

In this context, the central software engineering challenge consists in handling **diversity** from variability in requirements and design to heterogeneous and dynamic execution environments. In particular, this requires considering that the software system must adapt, in unpredictable yet valid ways, to changes in the requirements and environment. Conversely, explicitly handling diversity is a great opportunity to allow software to spontaneously explore alternative design solutions. Concretely, we want to provide software engineers with the following abilities:

- to characterize an “envelope” of possible variations;
- to compose envelopes (to discover new macro envelopes in an opportunistic manner);
- to dynamically synthesize software inside a given envelop.

The major scientific objective that we must achieve to provide such mechanisms for software engineering is summarized below:

Scientific objective for DiverSE:

To automatically **compose and synthesize software diversity** from design to runtime to **address unpredictable evolution of software-intensive systems**

Software product lines and associated variability modeling formalisms represent an essential aspect of software diversity, which we already explored in the past, and this aspect stands as a major foundation of DiverSE’s research agenda. However, DiverSE also exploits other foundations to handle new forms of diversity: type theory and models of computation for the composition of languages; distributed algorithms and pervasive computation to handle the diver-

sity of execution platforms; functional and qualitative randomized transformations to synthesize diversity for robust systems.

▲ If required, DiverSE’s scientific background is available online ¹.

2.3 Research axis

Figure 2 illustrates the four dimensions of software diversity, which form the core research axis of DiverSE: the **diversity of languages** used by the stakeholders involved in the construction of these systems; the **diversity of features** required by the different customers; the **diversity of runtime environments** in which software has to run and adapt; the **diversity of implementations** that are necessary for resilience through redundancy. These four axes share and leverage the scientific and technological results developed in the area of model-driven engineering in the last decade. This means that all our research activities are founded on sound abstractions to reason about specific aspects of software systems, compose different perspectives and automatically generate parts of the system.

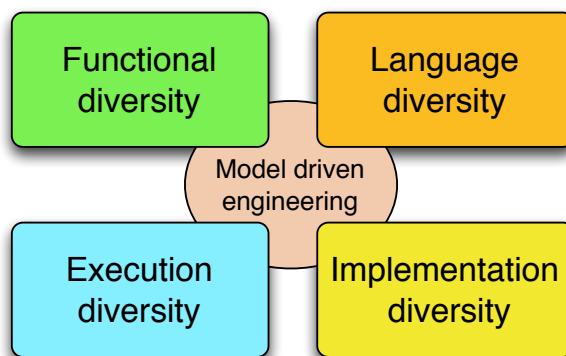


Figure 2: The four research axes of DiverSE, which rely on a MDE scientific background

2.4 Research Axis 1: Software Language Engineering

2.4.1 Personnel

Permanent fellows: M. Acher, O. Barais, B. Baudry A. Blouin, B. Combemale, J.-M. Jézéquel, D. Vojtisek.

Postdocs: J. A. Galindo, Elyes Cherfa.

PhD students: E. Bousse, F. Coulon, T. Degueule, P. Jeanjean, M. Leduc, D. Leroy, G. Le Moulec, D. Méndez-Acuña, G. Jouneaux

Research engineers: R. Belafia, R. Lefeuvre

2.4.2 Project-Team Positioning

The engineering of systems involves many stakeholders, each with their own domain of expertise. Hence more and more organizations are adopting Domain Specific Modeling Languages (DSMLs) to allow domain experts to express solutions directly in terms of relevant domain concepts [Sch06, FR07]. This new trend raises new challenges about designing DSMLs, evolving a set of DSMLs and coordinating the use of multiple DSLs for both DSL designers and DSL users.

¹INRIA asks the team members to keep the report under 40 pages. We have briefly presented some of the results without providing details. We will indicate in the report how to access an extended version of some sections if it is helpful to the reviewers.

Challenges

Reusability of software artifacts is a central notion that has been thoroughly studied and used by both academics and industrials since the early days of software construction. Essentially, designing reusable artifacts allows the construction of large systems from smaller parts that have been separately developed and validated, thus reducing the development costs by capitalizing on previous engineering efforts. However, it is still hardly possible for language designers to design typical language artifacts (e.g. language constructs, grammars, editors or compilers) in a reusable way. The current state of the practice usually prevents the reusability of language artifacts from one language to another, consequently hindering the emergence of real engineering techniques around software languages. Conversely, concepts and mechanisms that enable artifacts reusability abound in the software engineering community.

Variability in modeling languages occur in the definition of the abstract and concrete syntax as well as in the specification of the language’s semantics. The major challenges met when addressing the need for variability are: (i) to set principles for modeling language units that support the modular specification of a modeling language; and (ii) to design mechanisms to assemble these units into a complete language, according to the set of authorized variation points for the modeling language family.

A new generation of complex software-intensive systems (for example smart health support, smart grid, building energy management, and intelligent transportation systems) gives new opportunities for leveraging modeling languages. The development of these systems requires expertise in diverse domains. Consequently, different types of stakeholders (e.g., scientists, engineers and end-users) must work in a coordinated manner on various aspects of the system across multiple development phases. DSMLs can be used to support the work of domain experts who focus on a specific system aspect, but they can also provide the means for coordinating work across teams specializing in different aspects and across development phases. The support and integration of DSMLs leads to what we call **the globalization of modeling languages**, *i.e.* the use of multiple languages for the coordinated development of diverse aspects of a system. One can make an analogy with world globalization in which relationships are established between sovereign countries to regulate interactions (e.g., travel and commerce related interactions) while preserving each country’s independent existence.

Scientific objectives We address reuse and variability challenges through the investigation of the time-honored concepts of substitutability, inheritance and components, evaluate their relevance for language designers and provide tools and methods for their inclusion in software language engineering. We will develop novel techniques for the modular construction of language extensions with support to model syntactical variability. From the semantics perspective, we investigate extension mechanisms for the specification of variability in operational semantics, focusing on static introduction and heterogeneous models of computation. The definition of variation points for the three aspects of the language definition provides the foundations for the novel concept Language Unit (LU) as well as suitable mechanisms to compose such units.

We explore the necessary breakthrough in software languages to support modeling and simulation of heterogeneous and open systems. This work relies on the specification of executable domain specific modeling languages (DSMLs) to formalize the various concerns of a software-intensive system, and of models of computation (MoCs) to explicitly model the concurrency, time and communication of such DSMLs. We develop a framework that integrates the necessary foundations and facilities for designing and implementing executable and concurrent domain-specific modeling languages. This framework also provides unique features to specify composition operators between (possibly heterogeneous) DSMLs. Such specifications are amenable to support the edition, execution, graphical animation and analysis of heterogeneous models. The objective is to provide both a significant improvement to MoCs and DSMLs design and implementation and to the simulation based validation and verification of complex systems.

We see an opportunity for the automatic diversification of programs’ computation semantics, for example through the diversification of compilers or virtual machines. The main impact of this artificial diversity is to provide flexible computation and thus ease adaptation to different execution conditions. A combination of static and dynamic analysis could support the identification of what we call *plastic computation zones* in the code. We identify different categories of such zones: (i) areas in the code in which the order of computation can vary (e.g., the order in which a block of sequential statements is executed); (ii) areas that can be removed, keeping the essential functionality [SDMHR11] (e.g., skip some loop iterations); (iii) areas that can be replaced by alternative code (e.g., replace a try-catch by a return statement). Once we know which zones in the code can be randomized, it is necessary to modify the model of computation to leverage the computation plasticity. This consists in introducing variation points in the interpreter to reflect the diversity of models of computation. Then, the choice of a given variation is performed randomly at run time.

2.4.3 Scientific Achievements

We developed our scientific contributions related to software language engineering through three axes: software language foundations; software language development approaches and Integrated Development Environments (IDE); software language applications. We developed in a book [190] these axes to guide engineers in handling MDE and SLE concepts and toolings.

Software Language Foundations We proposed in [39, 193] a disciplined approach that leverages type groups’ polymorphism to provide an advanced type system for manipulating models, in a polymorphic way. This type system complements the Melange language workbench [DCB⁺15] and is seamlessly integrated into the Eclipse Modeling Framework (EMF) [SBMP08]. This research work is integrated within the Gemoc Studio [87], which is now an [Eclipse project](#). The PhD student involved in those work is one of the 2016 Grand Finals winners of the ACM’s Student Research Competition. The research works on a new typing system of languages permitted to work on the problem of **composition, extension, and reuse** of software languages. We introduced the *Language Extension Problem* as a way to better qualify the scope of the challenges related to language extension and composition [52]. We believe the *Language Extension Problem* will drive future research in SLE, the same way the original *Expression Problem* helped to understand the strengths and weaknesses of programming languages. We also stipulated the existence of a unifying framework that reduces all structural composition operators to structural merging, and all composition operators acting on discrete behaviors to event scheduling [48]. This has been established on the basis of previous formal description of such operators [45]. We then proposed a new language implementation pattern, named REVISITOR, that enables independent extensibility of the syntax and semantics of metamodel-based software languages with incremental compilation and without anticipation [133]. Following, we introduced a non-intrusive approach to modular development of language concerns with well-defined interfaces that can be composed modularly at the specification and implementation levels [134] (**awarded by the best artefact award at SLE 2018**). The goal of modular language development is to enable the definition of new languages as assemblies of pre-existing ones. Regarding reuse, we designed a high-level classification on the ability of the current reuse approaches for model transformations across different metamodels [96, 28] (awarded by the **best paper award at ICMT 2018**), and introduced a conceptual framework to foster reuse in modeling [124]. Following a bottom-up approach, we also analysed existing software language artefacts to: enable reuse of software language artefacts through the definition of language modules which can be later put together to build up new DSLs [60]; design a methodology for isolating Wikipedia’s articles about software languages and based on article’s features [114]. Regarding executable DSLs, we propose a metalanguage for complementing the definition of executable DSLs with explicit behavioral interfaces to enable external tools to interact with executed models in a unified

way [55]. We thus propose a runtime monitoring generic approach for executable DSLs [56], and more recently we propose a language-agnostic, unifying framework for runtime monitoring and logging, and demonstrate how it can be used to define loggers, runtime monitors and combinations of the two, aka. moniloggers [139]. We proposed a novel generative approach that defines a multidimensional and domain-specific trace metamodel enabling the construction and manipulation of execution traces for models conforming to a given xDSML [27]. We then proposed a set of formally defined operators for analyzing execution traces [137]. Regarding debugging, we: proposed a generic omniscient debugger supported by efficient generic trace management facilities [26]; identified temporal behavioral patterns that associate debugging activities with build success, which corroborates the positive impact of debugging practices on software development [175]. Regarding performance of executable DSL, little attention has been given to the performance of DSL interpreters. In [53], we systematically exploit the domain-specific information of language specifications to derive optimized Truffle-based language interpreters executed over the GraalVM. Following, we developed an approach for the concurrent execution of heterogeneous models [98]. The approach relies on an explicit model of concurrency and domain-specific actions with a well-defined protocol between them reified through explicit domain-specific events. We also investigate the concept of *self-adaptable languages* [119, 118]. While over recent years self-adaptation has become a concern for many software systems that have to operate in complex, software languages do not capitalize on monitored usage data of a language and its modeling environment, and do not use dedicated self-adaptation concerns. To address these issues, this paper introduces the concept of *Self-Adaptable Language* to abstract the feedback loops at both system and language levels.

Finally, we proposed a novel technique for processing user interactions [23] (at IEEE TSE). This novel technique permits the creation of highly interactive language environments.

Software Language development approaches and IDEs The novel concepts we detailed in the previous section consists of a common base for working on the next generations of DSL development approaches and DSL IDEs. Regarding software Language development approaches, in the new ideas paper [101], awarded as the **best new ideas paper at SLE 2018**, we envisioned a language engineering approach enabling (i) language users to manipulate language constructs in the most appropriate shape according to the task at hand, and (ii) language designers to combine the strengths of different technologies for a single DSL.

Regarding DSL IDEs, IDEs are evolving from monolithic desktop applications towards cloud-native applications with the aim to relocate the language services provided by an IDE on distant servers. We first conducted our experiment on the microservicization process of the Cloud-Based graphical modeling workbench Sirius Web [88]. We aimed to identify the technical challenges related to applications with similar properties, and provide insights for practitioners to migrate their similar applications towards microservices. In [100], we also explored the modularization of all language services to support their individual deployment and dynamic adaptation within an IDE. New languages appear regularly offering unique constructs and supported by dedicated services to be offered as new capabilities in IDEs. This trend leads to the multiplication of new protocols, hard to combine and possibly incompatible. We presented in [117] an approach that can make use of these specifications in order to deploy an IDE as a set of coordinated, individually deployed, language capabilities (e.g., microservice choreography). IDEs went from directly supporting languages to protocols, and we envision in this paper the next step: *IDE as Code*, where language protocols are created or inferred on demand and serve as support of an adaptation loop taking in charge of the (re)configuration of the IDE. In [116], we proposed an approach to automatically generate interactive computer programming environments from existing specifications of textual interpreted DSLs. The approach provides abstractions to complement the DSL specification, and combines static analysis and language transformations to automate the transformation of the language syntax, the execution state and the execution semantics. Closely related, in [180] we proposed an approach to REPL (Read-eval-print-loops)

interpreters. The obtained REPLs can be generically turned into an exploring interpreter, to allow exploration of the user’s interaction.

Provide practitioners with usable DSL environments is challenging. We first proposed an approach that focuses on easing the production of documentation of textual DSLs [51, 11]. We proposed a model-driven approach that relies on DSL artifacts to extract information required to build documentation. We also investigate live modeling, an important technique to edit behavioral models while being executed and helps in better understanding the impact of a design choice. We developed Live-UMLRT [85], a tool that supports live modeling of UML-RT models when they are executed by code generation. We also investigated modeling in the context of state machine models and code generation [20]. Finally, the ever-growing complexity of systems, the growing number of stakeholders, and the corresponding continuous emergence of new domain-specific modeling abstractions has led to significantly higher cognitive load on modelers. There is an urgent need to provide modelers with better modeling tools and processes. We developed roadmaps for: socio-technical coordination in the context of heterogeneous modeling [91] and of IoT systems [75]; intelligent modeling assistants [158, 61].

2.4.4 Software Language Applications

Application to Data-Centric Applications The ever increasing availability of data lead complex systems to integrate them all along the life cycle, from design to runtime. In [30], we introduce a conceptual reference framework – the Models and Data (MODA) framework – to support a data-centric and model-driven approach for the integration of heterogeneous models and their respective data for the entire life-cycle of socio-technical systems. We also explored the consideration of the time dimension, both for design [90] and for prediction [143, 142].

Application to DevOps and Digital Twins. Models open opportunities to offer a smooth continuum from design to runtime. In this context, we explored the opportunities for engineering digital twins [92], and to promote DevOps practices at the model level [191].

Application to Scientific Computing and Sustainability. Trading off some accuracy for better performances in scientific computing in general is an appealing approach to ease the exploration of various alternatives on complex simulation models. We proposed in [173] a new approximate computing technique, aka. loop aggregation, which consists in automatically reducing the main loop of a simulation model by aggregating the corresponding spatial or temporal data. Moreover, in [57], we investigate the different levels of abstraction, linked to the diverse artifacts of the scientific software development process, a software language can propose, and the V&V facilities associated to the corresponding level of abstraction the language can provide to the user. We aim to raise awareness among scientists, engineers and language providers on their shared responsibility in developing reliable scientific software. Finally, sustainability has emerged as a concern of central relevance. As a wicked problem, it poses challenges to business-as-usual in many areas, including that of modeling. In [47, 99] we address a question at the intersection of model-driven engineering and sustainability research: How can we better support sustainability by bringing together model-driven engineering, data, visualization and self-adaptive systems, to facilitate engagement, exploration, and understanding of the effects that individual and organizational choices have on sustainability?

Application to High-Performance Computing. In [54], we discuss the main lessons learned to be considered for conducting future projects in the field of HPC, and the remaining challenges that are worth being included in the road-map of the MDE community.

Application to Industry 4.0. Industry 4.0 integrates cyber-physical systems with the IoT to optimize the complete value-added chain. Successfully applying Industry 4.0 requires the cooperation of various stakeholders from different domains. We aim to assess the use of modeling in Industry 4.0 through the lens of modeling languages in a broad sense by conducting in [71] a systematic mapping study through which we developed an updated map of the research landscape on modeling languages and techniques for Industry 4.0.

Application to Virtual Reality. Due to the nature of Virtual Reality (VR) research, conducting experiments in order to validate the researcher’s hypotheses is a must. However, the development of such experiments is a tedious and time-consuming task. In [131], we propose to make this task easier, more intuitive and faster with a method able to describe and generate the most tedious components of VR experiments.

Application to Games. In [138], we present an approach to complement an operational semantics for handling stimuli, and by automatically generating a complete behavioral language interface from this augmentation. We demonstrate how it can be used to implement a Pac-Man DSL enabling to create and play Pac-Man games.

Application to HPC. In [135], we introduce NabLab, a full-fledged industrial environment for scientific computing and High-Performance Computing (HPC), involving several metamodels and grammars. Beyond the description of an industrial experience of the development and use of tool-supported DSLs, we report in this paper our lessons learned, and demonstrate the benefits from usefully combining metamodels and grammars in an integrated environment.

2.4.5 Collaborations

During this period, we worked with CEA (DSL for HPC), CWI (agility in language engineering), McGill (model reuse and self-adaptable languages), Aachen (MDE for industry 4.0), TU Wien (model executability), Lancaster University (MDE for environmental sciences), JKU Linz (co-evolution, and MDE for DevOps and digital twins), TU Eindhoven (MDE for DevOps and digital twins), Univ. L’alquila (MDE for DevOps and digital twins) and ETS Montreal (MDE for DevOps and digital twins). We also had a collaboration internally at Inria with the team Hybrid (usability in DSLs), and with the environmental sciences labs OSUR at University of Rennes 1.

2.4.6 External support

The work has been supported by bilateral collaboration with industry (Inria/Safran GLOSE, Inria/CEA Debug4Science, CIFRE Obeo, UR1/DGA Family, FPML and LangComponent), collaborative projects (IDM4SCO, OneWay, IPSCo, Clarity), international associate teams (ALE, Emma), and two French PhD grants (MESR).

2.4.7 Self Assessment

In this research axis, we conducted foundational and experimental research activities leading to publications in both top tier conferences and journals (*e.g.*, IEEE Software/Computer, Communication of the ACM, SoSym), as well as more specialized venues (*e.g.*, ACM SIGPLAN SLE or IEEE/ACM SIGSOFT MODELS). We developed a strong academic leaderships (deputy editor in chief at JOT, chair of the steering committee at SLE, associate editor at SOSyM, member of the steering committee at MODELS...), and provided large efforts to animate the community (*e.g.*, conferences and Dagstuhl/Bellairs workshops organisation). We also trained numerous PhD Students, all now either in academia (*e.g.*, University and CNRS) or industry.

Moreover, we devoted important efforts in transferring our research results, into education (*e.g.*, creation of specific supports for advanced courses), towards a more general audience (*e.g.* book publication [190]) and to industry (*e.g.*, creation and animation of the open-source research consortium GEMOC, together with the development of the Eclipse GEMOC Studio).

Finally, not only we continued our longstanding collaborations in the domain of systems engineering, but we also investigated new application domains to offer a broader impact to our research activities (cf. Section 2.4.4). In particular, we developed a new expertise in scientific computing, both for engineering (Safran, CEA) and environmental sciences (OSUR, Lancaster University).

2.5 Research Axis 2: Variability modeling

2.5.1 Personnel

Permanent fellows: M. Acher, J.-M. Jézéquel, Djamel E. Khelladi, A. Blouin, B. Combemale, O. Barais, B. Baudry

Postdocs: J. A. Galindo, X. Ternava, J. Pereira

PhD students: L. Lesoil, H. Martin, Q. Plazar, P. Temple

2.5.2 Project-Team Positioning

The systematic modeling of variability in software systems has emerged as an effective approach to document and reason about software evolution and heterogeneity . Variability modeling characterizes an “envelope” of possible software variations. The industrial use of variability models and their relation to software artifact models require a complete engineering framework, including tools for composition, decomposition, analysis, configuration and artifact derivation, refactoring, re-engineering, extraction, and testing. This framework can be used both to tame imposed diversity and to manage chosen diversity.

Challenges A fundamental problem is that the **number of variants** can be exponential in the number of options (features). Already with 300 boolean configuration options, approximately 10^{90} configurations exist – more than the estimated count of atoms in the universe. Domains like automotive or operating systems have to manage more than 10000 options (e.g., Linux). Practitioners face the challenge of developing billions of variants. It is easy to forget to ensure a necessary constraint, leading to the synthesis of unsafe variants, or to under-approximate the capabilities of the software platform. Scalable modelling techniques are therefore crucial to specify and reason about an extremely large set of variants.

Model-driven development supports two approaches to deal with the increasing number of concerns in complex systems: multi-view modeling, *i.e.* when modeling each concern separately, and variability modeling. However, there is little support to combine both approaches consistently. Techniques to integrate both approaches must enable the construction of a consistent set of views and variation points in each view.

The design, construction and maintenance of software families have a major impact on **software testing**. Among the existing challenges, we can cite: the selection of test cases for a specific variant; the evolution of test suites with integration of new variants; the combinatorial explosion of the number of software configurations to be tested. Novel model-based techniques for test generation and test management in a software product line context are needed to overcome state-of-the-art limits we already observed in some projects.

Scientific objectives We aim at developing scalable reasoning techniques to **automatically analyze** variability models and their interactions with other views on the software intensive system (requirements, architecture, design, code). These techniques provide two major advancements in the state of the art: (1) an extension of the semantics of variability models in order to enable the definition of attributes (*e.g.*, cost, quality of service, effort) on features and to include these attributes in the reasoning; (2) an assessment of the consistent specification of variability models with respect to system views (since variability is orthogonal to system modeling, it is currently possible to specify the different models in ways that are semantically meaningless). The former aspect of analysis is tackled through constraint solving and finite-domain constraint programming, while the latter aspect is investigated through automatic search-based and learning-based techniques for the exploration of the space of interaction between variability and view models.

We aim at developing procedures to **reverse engineer** dependencies and features’ sets from existing software artefacts – be it source code, configuration files, spreadsheets (e.g., product

comparison matrices) or requirements. We expect to scale up (e.g., for extracting a very large number of variation points) and guarantee some properties (e.g., soundness of configuration semantics, understandability of ontological semantics). For instance, when building complex software-intensive systems, textual requirements are captured in very large quantities of documents. In this context, adequate models to formalize the organization of requirements documents and automated techniques to support impact analysis (in case of changes in the requirements) have to be developed.

2.5.3 Scientific Achievements

Modeling variability. We contribute to a set techniques and formalisms to specify models of variability. This axis mainly focuses on scenarios in which persons (domain experts, developers, testers, etc.) elaborate and write variability. This is in contrast with the other reverse engineering and learning axis in which variability is automatically obtained, refined or augmented.

The contribution "Modeling Variability in the Video Domain: Language and Experience Report" [19] reports on our experience in modelling variability in the video domain. We detail the design of the VM language with advanced constructs in such a way video experts can comprehensively express variability information. We show the lack of standard variability languages and basic feature models. It eventually leads to the development of the MOTIV industrial generator for synthesizing a diverse of realistic video variants in a controlled way.

In [132], we address the problem of exploring numerous architectural alternatives until choosing the most adequate variant. The work lies in a systems engineering context and is a collaboration with Thales. The decision-making process is most of the time a manual, time-consuming, and error-prone activity. The exploration and justification of architectural solutions is ad-hoc and mainly consists in a series of trial and error on the modeling assets. In this contribution, we report on an industrial case study in which we apply variability modeling techniques to automate the assessment and comparison of several candidate architectures (variants). We use and extend the Common Variability Language (CVL). Beyond variant selection automation improvement, these experiment results highlight that the approach improves rationality in the assessment and provides decision making arguments when selecting the preferred variants.

In [164], we introduce featured model types in order to transpose the product line paradigm at the metamodel level, where reusable assets are formed by metamodel and transformation fragments and "products" are reusable language building blocks (model types). The intent is to concisely model variability amongst metamodeling elements, enabling configuration, automated analysis, and derivation of tailored model types.

In [125], we present a formal analysis framework to analyze a family of platform products w.r.t. real-time properties. First, we propose an extension of the widely-used feature model, called Property Feature Model (PFM), that distinguishes features and properties explicitly. Second, we present formal behavioral models of components of a real-time scheduling unit such that all real-time scheduling units implied by a PFM are automatically composed to be analyzed against the properties given by the PFM. We apply our approach to the verification of the schedulability of a family of scheduling units using the symbolic and statistical model checkers of Uppaal.

Reverse engineering variability. We contribute to a set methods and techniques to reverse engineer models of variability. The goal is to create variability representations of artefacts in another form or at a higher level of abstraction. Many kinds of artefacts (languages, tabular data, etc.) are targeted.

In [60, 148, 149], we propose a reverse engineering technique to identify commonality and variation points out of language variants. Our approach receives a set of DSL variants that are used to automatically recover a language modular design and to synthesize the corresponding variability models. The validation is performed in a project involving industrial partners that

required three different variants of a DSL for finite state machines. This validation shows that our approach is able to correctly identify commonalities and variability.

In [21], we show how to synthesize product comparison matrices (PCMs) out of informal product descriptions. Individual products are usually described in natural language (e.g., English) within textual data that are poorly structured and ambiguous. The challenge is to capture qualitative and quantitative information about the features of products and then synthesize a PCM. We develop natural language processing techniques to achieve this goal. We provide empirical evidence that there is a potential to complement or even refine technical information of products thanks to our extraction. The evaluation insights drive the design of the *MatrixMiner*, a web environment with an interactive support for synthesizing, visualising and editing PCMs.

Besides, we contributed to a large community involved in reverse engineering variability (see, e.g., the REVE workshops², co-organized with the SPLC conference).

Testing and sampling variability. Many approaches for testing configurable software systems start from the same assumption: it is impossible to test all configurations. This motivated the definition of variability-aware abstractions and sampling techniques to cope with large configuration spaces. Yet, there is no theoretical barrier that prevents the exhaustive testing of all configurations by simply enumerating them, if the effort required to do so remains acceptable. Not only this: we believe there is much to be learned by systematically and exhaustively testing a configurable system. In a case study [42, 111], we report on the first ever endeavour to test all possible configurations of an industry-strength, open source configurable software system, JHipster, a popular code generator for web applications. We built a testing scaffold for the 26,000+ configurations of JHipster using a cluster of 80 machines during 4 nights for a total of 4,376 hours (182 days) CPU time. We find that 35.70% configurations fail and we identify the feature interactions that cause the errors. We show that sampling strategies (like dissimilarity and 2-wise): (1) are more effective to find faults than the 12 default configurations used in the JHipster continuous integration; (2) can be too costly and exceed the available testing budget. We cross this quantitative analysis with the qualitative assessment of JHipster’s lead developers.

This study shows that *sampling* techniques are of prior importance. The challenge is to generate valid configurations that respect constraints while meeting a certain criterion. Uniform random sampling is a strong baseline and is useful in many testing scenarios (but also learning scenarios, see hereafter). In *Uniform Sampling of SAT Solutions for Configurable Systems: Are We There Yet?* [166], we show that state-of-the-art solutions either do not scale or are not uniform. Much more research is needed to have scalable and effective sampling strategies, especially for large variability spaces.

The study *Sampling Effect on Performance Prediction of Configurable Systems: A Case Study* [83] (**Best paper award at ICPE 2019**) shows that there is no single “dominant” sampling strategy even for the same configurable system. Instead, different strategies perform best on different inputs and non-functional properties, further challenging practitioners and researchers.

In [67] we propose to apply so-called “Multimorphic testing” and empirically assess the effectiveness of performance test suites of software systems coming from various domains. By analogy with mutation testing, our core idea is to leverage the typical configurability of these systems, and to check whether it makes any difference in the outcome of the tests: i.e., are some tests able to “kill” underperforming system configurations? More precisely, we propose a framework for defining and evaluating the coverage of a test suite with respect to a quantitative property of interest. Such properties can be the execution time, the memory usage or the success rate in tasks performed by a software system. This framework can be used to assess whether a new test case is worth adding to a test suite or to select an optimal test suite with respect to a property of interest. We evaluate several aspects of our proposal through three empirical studies

²<http://reveworkshop.github.io/>

carried out in different fields: object tracking in videos, object recognition in images, and code generators.

Learning variability. We contribute to a set of methods and techniques based on supervised, statistical machine learning to model variability constraints and non-functional properties (performance) of a configurable system.

In [205, 145] we perform a systematic review of the rich literature related to the learning of software configuration spaces. We report on the different application objectives (e.g., performance prediction, configuration optimization, constraint mining), use cases, targeted software systems and application domains. We review the various strategies employed to gather a representative and cost-effective sample. We describe automated software techniques used to measure functional and non-functional properties of configurations. We classify machine learning algorithms and how they relate to the pursued application. Finally, we also describe how researchers evaluate the quality of the learning process.

The work *Using Machine Learning to Infer Constraints for Product Lines* [179] was the starting point of our journey. We describe a learning approach to find subtle constraints of an industrial video generator used in the MOTIV project. The motivation is that despite important engineering effort the MOTIV generator synthesizes sometimes bad video variants due to lack of constraints among parameters. Our solution samples the configuration space, trains with a decision tree, and then injects rules of the tree into the variability model. The seminal ideas were further developed in the context of Paul Temple’s PhD thesis. In [66], we extend this line of work along two perspectives: (1) the learning of constraints can be parameterized by an high-level, performance objective; (2) constraints among the contextual features and the software configuration space can be automatically synthesized.

In [144] (**Best paper award at SPLC 2021**), we compare six learning techniques: three variants of decision trees (including a novel algorithm) with and without the use of model-based feature selection. We first perform a study on 8 configurable systems considered in previous related works and show that the accuracy reaches more than 90%, and that feature selection can improve the results in the majority of cases. We then perform a study on the Linux kernel and show that these techniques perform as well as on the other systems. Overall, our results show that there is no one-size-fits-all learning variant (though high accuracy can be achieved): we present guidelines and discuss tradeoffs.

In [68, 178] we introduce the use of adversarial machine learning to enforce a configuration classifier or pinpoint problematic cases. It allows to diagnose prediction errors and take appropriate actions. We develop two adversarial configuration generators on top of state-of-the-art attack algorithms; these generators are capable of synthesizing configurations that are both adversarial and conform to logical constraints. We empirically assess our generators with two case studies: an industrial video synthesizer (MOTIV) and an industry-strength, open-source Web-app configurator (JHipster). For the two cases, our attacks yield (up to) a 100% misclassification rate without sacrificing the logical validity of adversarial configurations. This work lays the foundations of a quality assurance framework for learning-based software product lines.

In [78], we develop the VaryLaTeX tool to synthesize papers’ variants that meet constraints such as page limits. It is based on learning techniques to enforce constraints prior to the generation. In [84] we apply a learning-based process to mine constraints and prevent defects in the 3D printing domain.

In [203, 80, 58], we apply learning techniques to the Linux kernel. With now more than 15,000 configuration options, including more than 9,000 just for the x86 architecture, the Linux kernel is one of the most complex configurable open-source system ever developed. If all these options were binary and independent, that would indeed yield 2^{15000} possible variants of the kernel. Of course not all options are independent (leading to fewer possible variants), but some of them have tri-states values: yes, no, or module instead of simply boolean values (leading to more possible variants). The Linux kernel is mentioned in numerous papers about configurable systems and

machine learning for motivating the problem and the underlying approach. However, only a few works truly explore such a huge configuration space. In this line of work, we take up the Linux challenge either for configurations’ bug prevention or for predicting the binary size of a configured kernel. We also design a learning technique capable of transferring a prediction model among versions of Linux [58].

Teaching variability. We are co-leading a worldwide initiative³ for disseminating the constantly growing body of software product line knowledge. This repository aims at sharing and delivering teaching material related to variability, configurable systems or generative approaches. This initiative is the result of three international workshops that we have co-organized, together with several surveys. An outcome of work is the article *Teaching Software Product Lines: A Snapshot of Current Practices and Challenges* [18], presented at SIGCSE’18.

2.5.4 Collaborations

During this period, we worked with KTH (testing variability), SnT (sampling variability), University of Namur (testing, sampling, and adversarial learning of variability), University of Delft (testing variability), University of Sevilla (modeling and learning variability), JKU Linz (teaching variability).

2.5.5 External support

The work was mainly supported by ANR JCJC VaryVary, MOTIV (DGA rapid), ANR Soprano, SLIMFAST (DGA and Brittany region)

2.5.6 Self Assessment

Our publication record covers (1) the two main specialized events about variability: SPLC and VaMoS; (2) top-tier software engineering journals (TSE, EMSE, JSS). We won three awards (best paper awards at ICPE and SPLC, most influential paper at SLE). We are present in the steering committees of SPLC and VaMoS and have been program committee co-chairs of these events. We are organizing workshops or conducting tutorials on our research axis (teaching, reverse engineering, learning).

In the future, we plan to further submit to top-tier, general software engineering conferences though we feel more comfortable with top-tier journals. We also believe software variability can be applied in other computer science domains (e.g., security, artificial intelligence). Hence a future ambitious goal can be to broaden the scope of our contributions.

We are targeting important, well-established, complex, and active open-source software projects (JHipster, x264, Linux). Though our results are promising and at the state of art, we cannot claim we are at the point of integrating our results (e.g., prediction models) and having concrete impacts on developers and users. More research is definitely needed to understand the reasons of this situation and bridge the gap. Another important reason is that much more engineering support is needed to mature, integrate, and follow the rapid continuous evolution of these projects.

³<http://teaching.variability.io/>

2.6 Research Axis 3: Runtime configuration and deployment for software-defined network services

2.6.1 Personnel

Permanent fellows: O. Barais, B. Baudry, J. Bourcier, J.-M. Jézéquel, N. Plouzeau.

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2.6.2 Project-Team Positioning

Flexible yet dependable systems have to cope with heterogeneous hardware execution platforms ranging from smart sensors to huge computation infrastructures and data centers. Evolution possibilities range from a simple change in the system configuration to a major architectural redesign, for instance to support addition of new features or a change in the platform architecture (e.g., new hardware is made available, a running system switches to low bandwidth wireless communication, a computation node battery is running low, etc). In this context, we need to devise formalisms to reason about the impact of an evolution and about the transition from one configuration to another. It must be noted that this axis focuses on the use of models to drive the evolution from design time to runtime. Models will be used to (i) systematically define predictable configurations and variation points through which the system will evolve; (ii) develop behaviors necessary to handle unforeseen evolution cases.

Challenges The main challenge is to provide new homogeneous architectural modelling languages and efficient techniques that enable continuous software reconfiguration to react to changes. This work handles the challenges of handling the diversity of runtime infrastructures and managing the cooperation between different stakeholders. More specifically, the research developed in this axis targets the following dimensions of software diversity.

Platform architectural heterogeneity induces a first dimension of imposed diversity (type diversity). *Platform reconfiguration* driven by changing resources define another dimension of diversity (deployment diversity). To deal with these imposed diversity problems, we will rely on model based runtime support for adaptation, in the spirit of the dynamic distributed component framework developed by the Triskell team. Since the runtime environment composed of distributed, resource constrained hardware nodes cannot afford the overhead of traditional runtime adaptation techniques, we investigate the design of novel solutions relying on Models@runtime and on specialized tiny virtual machines to offer resource provisioning and dynamic reconfiguration.

Diversity can also be an asset to optimize software architecture. Architecture models must integrate multiple concerns in order to properly manage the deployment of software components over a physical platform. However, these concerns can contradict each other (e.g., accuracy and energy). In this context, we investigate automatic solutions to explore the set of possible architecture models and to establish valid trade-offs between all concerns in case of changes.

Scientific objectives Automatic synthesis of optimal software architectures. Implementing a service over a distributed platform (e.g., a pervasive system or a cloud platform) consists in deploying multiple software components over distributed computation nodes. We aim at designing search-based solutions to (i) assist the software architect in establishing a good initial architecture (that balances between different factors such as cost of the nodes, latency, fault tolerance) and to automatically update the architecture when the environment or the system itself change. The choice of search-based techniques is motivated by the very large number of possible software deployment architectures that can be investigated and that all provide different trade-offs between qualitative factors. Another essential aspect that is supported

by multi-objective search is to explore different architectural solutions that are not necessarily comparable. This is important when the qualitative factors are orthogonal to each other, such as security and usability for example.

Flexible software architecture for testing and data management. As the number of platforms on which software runs increases and different software versions coexist, the demand for testing environments also increases. For example, the number of testing environments to test a software patch or upgrade is the product of the number of execution environments the software supports and of the number of coexisting versions of the software. Based on our first experiment on the synthesis of cloud environment using architectural models, our objective is to define a set of domain specific languages to catch the requirement and to design cloud environments for testing and data management of future internet systems from data centers to things. These languages will be interpreted to support dynamic synthesis and reconfiguration of a testing environment.

Runtime support for heterogeneous environments. Execution environments must provide a way to account for or reserve resources for applications. However, current execution environments such as the Java Virtual Machine do not clearly define a notion of application: each framework has its own definition. For example, in OSGi an application is a component; in JEE an application is most of the time associated to a class loader; in the Multi-Tasking Virtual machine an application is a process. The challenge consists in defining an execution environment that provides direct control over resources (CPU, memory, network, I/O), independently from the definition of an application. We propose to define abstract resource containers to account for and reserve resources on a distributed network of heterogeneous devices.

2.6.3 Scientific Achievements

Automatic synthesis of optimal software architectures.

Regarding this challenge, we keep working in the field of Models@runtime. The objective is to provide the appropriate abstraction at the modeling layer in order to simplify the reasoning and synthesis of the optimal software architecture. In this axis, one of the goals is to work on the shipping steps of the deployment phase, and the reconfiguration accessible to a whole development team. During the evaluation period, we worked in particular on the cloud computing domain and on the energy domain.

In the first one, we enhance existing models that could be used at runtime to improve resource usage in two domains: cloud computing [41, 110, 113, 103, 104, 38, 105, 86, 112, 155, 29, 22] and energy [213, 170, 169, 162].

In the cloud computing domain, we provide specific abstractions to cloud providers, in order to allow the reselling of unused resources to peers. Indeed, although cloud computing techniques have reduced the total cost of ownership thanks to virtualization, the average usage of resources (e.g., CPU, RAM, network, I/O) remains low. To address such issue, one may sell unused resources. Such a solution requires the cloud provider to determine the resources available and estimate their future use to provide availability guarantees. In this work, we propose a technique that uses machine learning algorithms (Random Forest, Gradient Boosting Decision Tree, and Long Short Term Memory) to forecast 24-hour of available resources at the host level. Our technique relies on the use of quantile regression to provide a flexible trade-off between the potential amount of resources to reclaim and the risk of SLA violations. In addition, several metrics (e.g., CPU, RAM, disk, network) are built to provide exhaustive availability guarantees. Our methodology is evaluated by relying on four in production data center traces, and our results show that quantile regression is relevant to reclaim unused resources. Our approach may increase the amount of savings up to 20% compared to traditional approaches [103, 104, 38, 105].

In the energy domain, we work at proposing models that could be used at runtime to improve self-consumption of renewable energies [213, 170, 169]. Self-consumption of renewable energies is defined as electricity that is produced from renewable energy sources, not injected to the

distribution or transmission grid or instantaneously withdrawn from the grid and consumed by the owner of the power production unit or by associates directly contracted to the producer. Designing solutions in favor of self-consumption for small industries or city districts is challenging. It consists in designing an energy production system made of solar panels, wind turbines, batteries that fit the annual weather prediction and the industrial or human activity. In this context, we define a domain specific modeling language designed to let domain experts run their own simulations at design time and at runtime [213, 170, 169].

Flexible software architecture for testing and data management.

To answer this challenge, we have shown the benefit of disposing of a configurable software architecture in order to exhaustively test different configurations of the same system [198]. In particular, we have proposed an approach to generate dedicated architectures to test different code generators for heterogeneous platforms [94, 6, 25, 93]. This approach is based on the notion of meta-morphic testing in order to avoid the definition of an oracle by a tester. Using learning techniques our approach builds a model of resource usage for each target platform and then uses classification techniques to decide when a code generator for one of the target platforms is out of its validity envelop regarding resources consumption. In continuation of this work, we have shown how it is possible to use the same type of technique in the domain of virtualized functions in order to detect bugs during a reconfiguration [197, 167]. The proposed approach builds a nominal resource usage model for a given virtualized function using learning techniques, and it can thus detect an error during a reconfiguration (dependencies update, deployment topologies update, etc.) by detecting an execution outside the nominal operating envelop. As a complement, we also show how we could trigger an internal reconfiguration⁴ in a testing environment in executing virtualized network functions under perturbation.

Runtime support for heterogeneous environments.

The Kevoree platform is the main result in which we have integrated the work done within this axis. This software platform provides an implementation in Java [153], in JavaScript [181] (in the browser or on the server), a support for the deployment of Docker components, a support for the deployment on embedded platforms such as Arduino micro-controllers. It offers a common abstraction layer allowing to describe in a declarative way the desired deployment. It has an execution platform and a development model for heterogeneous environments in order to interpret the desired configuration and control the local adaptations to be made. The reification through the notion of “group” of the coordination semantics of the adaptation allows to explain the behavior of each of these platforms. The Kevoree platform source amounts to 10,125 commits from 56 contributors, representing 1,065,549 lines of code.

During the evaluation period, we also extended the Models@runtime layer used within Kevoree. Indeed, the evolving complexity of adaptive systems impairs our ability to deliver anomaly-free solutions. Fixing these systems require a deep understanding on the reasons behind decisions that led to faulty or suboptimal system states. Developers thus need diagnosis support that trace system states to the previous circumstances –targeted requirements, input context– that had resulted in these decisions. However, the lack of efficient temporal representation limits the tracing ability of current approaches. To tackle this problem, we describe a novel temporal data model to represent, store and query decisions as well as their relationship with the knowledge (context, requirements, and actions). We validate our approach through a use case based on the smart grid at Luxembourg [157, 155, 156].

While developments around Kevoree have decreased somewhat over the past two years, it is worth noting that work on resource management has been actively pursued as part of the openstack open-source project through the collaboration with B-COM. The Watcher project⁵ is an implementation of an autonomic loop clearly in the spirit of runtime models. The industrial dynamics in the field of deployment has led to the creation of large audience projects such as K8S, the work around the modeling of resources around a Models@runtime approach has been

⁴reconfiguration bound to an autonomic self-healing loop within the system

⁵<https://wiki.openstack.org/wiki/Watcher>

conducted in this context [113, 103, 104, 86, 112].

2.6.4 Collaborations

During the evaluation period, we actively collaborated internally at INRIA with the EASE project-team (2 joint PhDs), Myriads (1 joint PhD), Wide [100] (common contribution), Spirals (project, persons and platform transfer between the two groups and many common publications). Through our activities in the cloud computing domain, we regularly interact with the STACK team (PhD students follow-up, informal workshop, ...). During this period, we also worked actively with B-COM, KTH, SINTEF, and SnT. It should be noted that several PhD students who worked on the Kevoree platform have founded the DataThings company, which has been growing rapidly for the last two years in Luxembourg (<https://datathings.com/>). We keep exchanging regularly with this spinoff.

2.6.5 External support

- Occiware
- FP7 STREP HEADS
- ADR Nokia
- BCOM (CIFRE)
- Orange (CIFRE + CRE)
- OKWind (CIFRE)
- H2020 ICT-10-2016 STAMP

2.6.6 Self Assessment

The *Runtime configuration and deployment for software-defined network services* axis bridges the gap between the domains of software engineering, systems engineering and distributed systems. Our will to find the right abstractions to capture the behavior of applications and execution platforms remains a key motivation to propose the right development model and the right management model for modern applications. Proposing our own deployment platform has allowed us to be a precursor on the notion of Models@runtime. During the evaluation period, we continued this work in order to understand how to build resource models at the heart of modern systems and how to use these models to optimize the functioning of a software system.

Some highlights of our contribution and results are:

- the publications in well-established conferences and journals (CCGRID, IEEE transactions on cloud computing, JSS, Models,...)
- the development of the Kevoree platform in the framework of a European project but also with several direct industrial partnerships
- The training of 7 PhD students in the field (all of them are now founders of innovative companies or tech leads in partner companies)

The ideas behind the notion of Models@runtime are now fully reflected in cloud orchestrators such as Kubernetes (K8S). In order to maximize the impact of our work, we have chosen to continue our work by integrating our current and future contributions within this platform. While the learning cost is huge and the granularity of the reconfiguration is higher compared to software reconfiguration primitives available in Kevoree, we benefit from a large spectrum of technical contributions from the community. During the evaluation period, we initiate the use of advanced deployment techniques for the security domain (through a partnership project called OneShot Software) and for the resilience and testing domain (see sub-axis 2). Further work on the problem of dynamic reconfiguration and deployment on heterogeneous platforms will be carried out mainly in the new #3 axis presented in the perspectives section.

2.7 Research Axis 4: Software implementation diversification

2.7.1 Personnel

Permanent fellows: O. Barais, B. Baudry, A. Blouin, B. Combemale, J.M. Jézéquel, D. Khelladi, N. Plouzeau, O. Zendra, Gurvan Le Guernic

Postdoc: N. Messe, A. Benenallam

PhDs: A. Hervieu, O. L. Vera-Pérez P. Temple, M. Boussaa, A. Gomès-Boix, P. Laperdrix, J. E. Dartois, Q. Le Dilavrec, Y. Ndiaye

Engineers: R. Lefeuvre, R. Bellafia

2.7.2 Project-Team Positioning

Open software-intensive systems have to evolve over their lifetime in response to changes in their environment. Yet, most verification techniques assume a closed environment or the ability to predict all changes. Dynamic changes and evolution cases thus represent a major challenge for these techniques that aim at assessing the correctness and robustness of the system. On the one hand, DiverSE will adapt V&V techniques to handle diversity imposed by the requirements and the execution environment, on the other hand we leverage diversity to increase the robustness of software in face of unforeseen situations. More specifically, we address the following V&V challenges.

Challenges One major challenge when building flexible and open yet dependable systems is that current software engineering techniques require architects to foresee all possible situations that the system will have to face. However, openness and flexibility also mean unpredictability: unpredictable bugs, attacks, environmental evolution, etc. Current fault-tolerance [Ran75] and security [FSA97] techniques provide software systems with the capacity of detecting accidental and deliberate faults. However, existing solutions assume that the set of bugs or vulnerabilities in a system does not evolve. This assumption does not hold for open systems, thus it is essential to revisit fault-tolerance and security solutions to account for diverse and unpredictable faults.

Diversity is known to be a major asset for the robustness of large, open, and complex systems (*e.g.*, economical or ecological systems). Following this observation, the software engineering literature provides a rich set of works that rely on implementation diversity in software systems in order to improve robustness to attacks or to changes in quality of service. These works range from N-version programming to obfuscation of data structures or control flow, and to randomization of instruction sets. An essential and active challenge is to support the automatic synthesis and evolution of software diversity in open software-intensive systems. There is an opportunity to further enhance these techniques in order to cope with a wider diversity of faults, by multiplying the levels of diversity in the different software layers that are found in software-intensive systems (system, libraries, frameworks, application). This increased diversity must be based on artificial program transformations and code synthesis, which increase the chances of exploring novel solutions, better fitted at one point in time. The biological analogy also indicates that diversity should emerge as a side-effect of evolution, to prevent over-specialization towards one kind of diversity.

Scientific objectives The main objective is to address one of the main limitations of N-version programming for fault-tolerant systems: the manual production and management of software diversity. Through automated injection of artificial diversity we aim at systematically increasing failure diversity and thus increasing the chances of early error detection at run-time. A fundamental assumption for this work is that software-intensive systems can be “good enough” [Rin12, ZMKR12].

Proactive program diversification. We aim at establishing novel principles and techniques that favor the emergence of multiple forms of software diversity in software-intensive systems, in conjunction with the software adaptation mechanisms that leverage this diversity. The main expected outcome is a set of meta-design principles that maintain diversity in systems and the experimental demonstration of the effects of software diversity. Higher levels of diversity in the system provide a pool of software solutions that can eventually be used to adapt to situations unforeseen at design time (bugs, crash, attacks, etc.). Principles of automated software diversification rely on the automated synthesis of variants in a software product line, as well as finer-grained program synthesis combining unsound transformations and genetic programming to explore the space of mutational robustness.

Multi-tier software diversification.

We name multi-tier diversification the technique of diversifying several application software components simultaneously. The novelty of our proposal, with respect to the software diversity state of the art, is to diversify the application-level code (for example, diversify the business logic of the application), focusing on the technical layers found in web applications. The diversification of application software code is expected to provide a diversity of failures and vulnerabilities in web server deployment. Web server deployment usually adopts a form of the Reactor architecture pattern, for scalability purposes: multiple copies of the server software stack, called request handlers, are deployed behind a load balancer. This architecture is very favorable to diversification, since by using the multiplicity of request handlers running in a web server we can simultaneously deploy multiple combinations of diverse software components. Then, if one handler is hacked or crashes the others should still be able to process client requests.

2.7.3 Scientific Achievements

Proactive program diversification. On this axis, much work has been done in the field of proactive diversity of software and software tests in order to improve the quality of tests but also to evaluate the test suite quality [36, 72, 37, 43]. Thus, within the framework of the European project Stamp ⁶, we have highlighted the interest of *extreme mutation* in order to better qualify the quality of existing test suites [72, 70, 183]. We have also worked on the use of self-repair techniques to improve existing tests [24, 34]. We have worked extensively on the notion of patch generation at runtime [35, 49], the qualification of test data by automated variant synthesis in the context of extreme mutation [NJW16]. We also propose a framework for defining and evaluating the coverage of a test suite with respect to a quantitative property of interest [67, 177].

Software evolution A second important aspect of automated diversification was to better understand the problems of co-evolution in software. Indeed, transforming a software artifact generally requires co-evolving associated artifacts. For example, transforming an abstract model requires co-evolving the generated code sometimes manually modified by the developer; transforming an API definition requires an evolution the client, which is sometimes developed using another programming language, etc. In this context, we started a project on the challenge of software co-evolution, thanks to the arrival of Djamel Eddine Khelladi in the team. With our first results we show how to co-evolve models and associated code [121, 44, 122, 50, 123] but also how to better understand the existing co-evolution in open source code repositories [128]. Another important work focused in detail on the natural evolutions found in binaries repositories in the Java community for example [89].

Multi-tier software diversification. This axis is the one that has probably evolved the most with respect to its initial objective. Several demonstrators have been built in the context of a partnership with Orange, aiming at demonstrating how to use adaptation techniques at the application architecture level in order to make several variants of the same application coexist.

⁶<https://www.stamp-project.eu/>

However, this study was conducted in the context of improving software security. While it was clear that software diversity improves the resilience of large systems, it was not clear how to provide evidence of its benefits for a single service. Thus, still in the context of the partnership with Orange, we worked on authentication in multi-tier applications and more generally on several aspects related to security with the arrival of Olivier Zendra in the DiverSE team.

Besides the Orange collaboration, we conducted studies on Maven artifacts that indicate that the immutability those artifacts does support a sustained level of diversity among versions of libraries in the repository [174]. We also conducted studies on browser fingerprint as an identification technique based on various information (cookies, hardware, software components) [182].

On the authentication axis, we have conducted studies on the openId Connect protocol and its use in the context of WebRTC session in order to show the difficulties of preserving the privacy of the user [32, 65, 33], we have worked on a language for the specification of authentication paths to support risk analysis associated with each authentication path [160]. We worked on the notion of browser finger printing both in a context of study of privacy [109, 107, 127, 126] but also in a context of its use for authentication [195]. This work had a notable impact in the community. Through the collaboration with the DGA, we have worked on the modeling of network packet filtering policies as well as their formalization in order to identify diversification possibilities [129, 207, 206, 130].

Finally, the arrival of Olivier Zendra allowed us to start looking at vulnerability and malware detection techniques in order to understand how they could be used in the context of advanced diversification issues [115, 151, 161, 168].

2.7.4 Collaborations

During the evaluation period, we actively collaborated internally at INRIA with the Spirals project team. We actively also work with Prof. Gildas Avoine at IRISA on browser finger printing. During this period, we also worked actively with B-COM, KTH, SINTEF. We also keep an active collaboration with Orange Labs and our partner [120, 44, 50, 49] at JKU, Austria.

2.7.5 External support

- Orange (3 * CIFRE + CRE)
- BCOM (CIFRE)
- H2020 ICT-10-2016 STAMP
- ANR JCJC x2

2.7.6 Self Assessment

This axis evolved over the period. This can be explained by significant human resources changes. With Benoit Baudry taking up his position at KTH, the arrival of Djamel Eddine Khelladi and Olivier Zendra, the two full-time researchers in the team, has allowed us to explore in greater detail the problems of co-evolution and to work more in the field of resilience and security. However, the academic results in this axis are excellent and well-published. Our work on test amplification is highly original while offering real industrial perspectives. Our work on browser finger printing had a real impact both at the academic and societal levels ⁷. The theme is out of the scope of DiverSE for the next period, as two non-permanent DiverSE persons working on this topic have now permanent positions within the Spirals Project Team (Walter Rudametkin and Pierre Laperdrix). The long-standing collaboration with Orange on architecture and authentication challenges allows DiverSE to work regularly and in confidence with the Orange Labs's *authentication research team*. The work on co-evolution lead by Djamel Eddine Khelladi already provides excellent publications, one ANR JCJC project and has led to several ongoing PhDs in the team. Finally, the arrival of Olivier Zendra sharing the DiverSE scientific background but bringing his skills in the cybersecurity domain opens many perspectives for the next period.

⁷Prix INRIA/CNILL 2018

2.8 Evolution of Research Directions During the Evaluation Period

At the start of the current evaluation period, our planned research directions were:

- Language diversity: Software Language Engineering.
- Functional diversity: Variability modeling.
- Execution diversity: Runtime configuration and deployment of heterogeneous and distributed services.
- Implementation diversity: Software test amplification

Most of our research directions were kept during the evaluation period.

On the first two axes, we have deepened the scientific proposal, allowing the emergence of new sub-axes. In particular, the work on micro-servicisation of language services is promising and it has become one the challenges of the next period. The targeted application domains also had a real impact on the software platforms developed within the Gemoc initiative. The work on the notion of deep-variability is also at the core of the next period. On the *Execution diversity* axis, we have mainly worked on the problem of resource management. A large part of the work was carried out in the field of cloud computing. No new PhD thesis was started in the last three years. The last PhD students working on execution diversity will complete their work at the end of 2021 or beginning of 2022. This leads to a restructuring of this axis for the next evaluation period. On the *Implementation diversity* axis, three major events could be highlighted. The leave of Benoit Baudry is not visible in the 2016-2021 period. Indeed, several of Benoit's doctoral students defended their thesis during the period, and they remain within the team. However, as for axis #3, no PhDs in the field of software testing has started in the last three years. As a major topic evolution we have started to work on co-evolution thanks to the arrival of Djamel as a CR CNRS lead. Similarly, the arrival of Olivier Zendra in the team has opened up the field of software security.

Evolution of Research Directions During the Evaluation Period

The work program has been followed for the period 2016-2021. However, we would like to take advantage of this evaluation to refactor the team organization for the next evaluation period. Section 5 details this team reorganization.

3 Knowledge Dissemination

3.1 Publications

	number from October 2016 to October 2021
PhD Theses	18
HDRs (*)	2
Journal papers	55
Conference papers	109
Conference proceedings	3
Book chapters	3
Books	1
General audience papers	1
Technical reports	12

(*) HDR: Habilitation à diriger des Recherches

DiverSE's publications policy:

Over this period, we have voluntarily adopted a strategy of "journal first" publications without necessarily starting with an acceptance in a conference. This strategy, which is not exclusive either, is mainly motivated by the possibility offered by the journals to use the different rounds of submissions to explain certain ideas in breakthrough.

Publications in Main Journals:

1. IEEE Trans. on Software Engineering: 3
2. Sosym: 10
3. JSS: 7
4. Empirical Software Engineering: 6
5. STVR: 1
6. CACM: 1
7. IST: 3
8. COLA (formerly COMLAN): 4
9. Transactions on Modularity and Composition: 1
10. Transactions on Cloud Computing: 1

Publications in Major Conferences:

1. ICSE: 1
2. ASE: 1
3. MODELS: 5
4. SLE: 7
5. IEEE Symposium on Security and Privacy (SnP): 2
6. International World Wide Web Conference (WWW): 1
7. SPLC: 11
8. MSR: 3
9. CCgrid: 1
10. ICMSE: 1
11. ICST: 1
12. ICPE: 1
13. VRST: 1

14. ICSE/NIER: 1
15. Onwards: 2
16. GPCE: 1
17. IJCAI: 1
18. Privacy Enhancing Technology (CSP): 1

Selection of Publications The following papers will be available on the evaluation website:

1. **Co-Evolving Code with Evolving Metamodels**, in [International Conference on Software Engineering \(ICSE\) 2020](#) [121].
2. **Empirical Assessment of Multimorphic Testing**, [IEEE Transactions on Software Engineering \(TSE\) 2019](#) [67].
3. **Omniscient Debugging for Executable DSLs**, [Journal of Systems and Software \(JSS\) 2018](#) [26].
4. **Interacto: A Modern User Interaction Processing Model**, [IEEE Transactions on Software Engineering \(TSE\) 2021](#) [23].
5. **Investigating Machine Learning Algorithms for Modeling SSD I/O Performance for Container-based Virtualization**, [IEEE Transactions on Cloud Computing 2020](#) [38].

▲ Due to space limitation, a short description of each paper is available [online](#)

3.2 Software

▲ Due to space limitation, we do not present all the tools developed by the team but we select only the most representative. A full list is available [online](#).

3.2.1 FAMILIAR

Keywords: Software line product, Configurators, Customisation

Functional Description: Familiar is an environment for large-scale product customisation.

From a model of product features (options, parameters, etc.), Familiar can automatically generate several million variants. These variants can take many forms: software, a graphical interface, a video sequence or even a manufactured product (3D printing). Familiar is particularly well suited for developing web configurators (for ordering customised products online), for providing online comparison tools and also for engineering any family of embedded or software-based products.

URL: <http://familiar-project.github.com>

Contact: Mathieu Acher

Participants: Aymeric Hervieu, Benoit Baudry, Didier Vojtisek, Edward Mauricio Alferez Salinas, Guillaume Bécan, Joao Bosco Ferreira-Filho, Julien Richard-Foy, Mathieu Acher, Olivier Barais, Sana Ben Nasr

Partners: CNRS, University Nice Cote d'Azur

INRIA taxonomy: research, partners, Its, leader.

Duration of the Development More than 10 years

3.2.2 GEMOC Studio

Name: GEMOC Studio

Keywords: DSL, Language workbench, Model debugging

Functional Description: The GEMOC Studio is an Eclipse package that contains components supporting the GEMOC methodology for building and composing executable Domain-Specific Modeling Languages (DSMLs). It includes two workbenches: The GEMOC Language Workbench: intended to be used by language designers (aka domain experts), it allows to build and compose new executable DSMLs. The GEMOC Modeling Workbench:

intended to be used by domain designers to create, execute and coordinate models conforming to executable DSMLs. The different concerns of a DSML, as defined with the tools of the language workbench, are automatically deployed into the modeling workbench. They parametrize a generic execution framework that provides various generic services such as graphical animation, debugging tools, trace and event managers, timeline.

URL: <http://gemoc.org/studio.html>

Authors: Didier Vojtisek, Benoît Combemale, Cédric Brun, François Tanguy, Joël Champeau, Julien DeAntoni, Xavier Crégut

Contacts: Benoît Combemale, Julien DeAntoni

Participants: Didier Vojtisek, Dorian Leroy, Erwan Bousse, Fabien Coulon, Julien DeAntoni

Partners: IRIT, ENSTA, I3S, OBEO, Thales TRT

INRIA taxonomy: research, community, lts, leader.

Duration of the Development More than 6 years

3.2.3 Descartes

Keywords: Software testing, Mutation analysis

Functional Description: Descartes evaluates the capability of your test suite to detect bugs using extreme mutation testing.

Descartes is a mutation engine plugin for PIT which implements extreme mutation operators as proposed in the paper *Will my tests tell me if I break this code?*.

URL: <https://github.com/STAMP-project/pitest-descartes>

Publications: [hal-01870976](#), [hal-01867423](#)

Contacts: Benoit Baudry, Oscar Luis Vera Perez, Olivier Barais, Martin Monperrus

Participants: Oscar Luis Vera Perez, Benjamin Danglot, Benoit Baudry, Martin Monperrus

Partner: KTH Royal Institute of Technology

INRIA taxonomy: research, community, basic.

Duration of the Development More than 3 years

3.2.4 Kevoree

Keywords: M2M, Dynamic components, Iot, Heterogeneity, Smart home, Cloud, Software architecture, Dynamic deployment

Functional Description: Kevoree is an open-source models@runtime platform to properly support the dynamic adaptation of distributed systems. Models@runtime basically pushes the idea of reflection one step further by considering the reflection layer as a real model that can be uncoupled from the running architecture (e.g. for reasoning, validation, and simulation purposes) and later automatically resynchronized with its running instance.

URL: <http://kevoree.org/>

Authors: Jean Emile Dartois, Aymeric Hervieu, Olivier Barais

Contact: Olivier Barais

Participants: Aymeric Hervieu, Benoit Baudry, Francisco-Javier Acosta Padilla, Inti Gonzalez Herrera, Ivan Paez Anaya, Jacky Bourgeois, Jean Emile Dartois, Johann Bourcier, Manuel Leduc, Maxime Tricoire, Mohamed Boussaa, Noël Plouzeau, Olivier Barais

INRIA taxonomy: research, partners, no future, leader.

Duration of the Development More than 5 years

3.2.5 amiunique

Name: amiunique

Keywords: Privacy, Browser fingerprinting

Functional Description: This web site aims at informing visitors about browser fingerprinting and possible tools to mitigate its effect, as well as at collecting data about the fingerprints

that can be found on the web. It collects browser fingerprints with the explicit agreement of the users (they have to click on a button on the home page). Fingerprints are composed of 17 attributes, which include regular HTTP headers as well as the most recent state of the art techniques (canvas fingerprinting, WebGL information).

URL: <https://amiunique.org/>

Authors: Pierre Laperdrix, Antonin Durey, Walter Rudametkin Ivey

Contacts: Benoit Baudry, Pierre Laperdrix

Partners: INSA Rennes, Université de Lille

INRIA taxonomy: research, universe, lts, instigator (previous leader and now managed by Spirals team).

Duration of the Development More than 3 years

3.2.6 Overall evaluation

GEMOC (which includes Melange and ALE) and Familiar will remain two core platforms of the team for the next evaluation period. We have aggregated and we keep aggregating the results of several PhD students into these two platforms. The maintenance and the evolution of AmIUnique are now taken in charge by the INRIA Spirals. Kevoree has brought many contributions including some libraries developed in the framework of Kevoree which are still used massively by other open source projects (*npmi* is still downloaded more than **20000 times** a week <https://www.npmjs.com/package/npmi>). However, on the deployment axis, we now come to place ourselves in the core of open-source project such as K8S to bring our idea to existing communities. The platforms developed within the framework of the STAMP project have given rise to numerous experiments by industrialists. Descartes is still at the heart of the continuous integration chain of various industrial players.

3.3 Technology Transfer and Socio-Economic Impact

During the period, members of DIVERSE had close collaborations with

- large companies like Safran, Nokia Bell Labs, Orange, Thales
- small and medium-sized enterprises (SME) like XWiki, Fabernovel, OKwind, Obéo,
- and Institute like DGA (Rennes), CEA (Saclay & Bruyères le chatel) or IRT B-COM.

The Heads FP7 project has led to a transfer to TellU SaS of ThingML in which we provide several valuable contributions. ALE is now supported by Obeo.

Most of our former PhD students or PostDocs are now R&D engineers in companies or startups such as Amazon, Mathworks, Orange, XWiki, MediaKind, Famoco, OKWind, SHARE NOW, Adobe, KUGU, ActiveEon, SopraSeria, EXFO or Couture Technologies.

We devoted leadership within the Open Source Foundation Eclipse. In particular, we initiated the only one research consortium hosted within the Eclipse Foundation (the GEMOC Research Consortium). It is a working group that brings together academia and industry on the topic of software language engineering.

Finally, we currently initiate a startup project on the basis of our work on language engineering in the context of systems engineering. The project is matured since early 2021, and we aim at starting the company early 2022.

3.4 Teaching

The DiverSE team bears the bulk of the teaching on Software Engineering at the University of Rennes 1 and at INSA Rennes, for the first year of the Master of Computer Science (Project Management, Object-Oriented Analysis and Design with UML, Design Patterns, Component Architectures and Frameworks, Validation & Verification, Human-Computer Interaction) and for the second year of the MSc in software engineering (Model driven Engineering, Aspect-Oriented

Software Development, Software Product Lines, Component Based Software Development, Validation & Verification, *etc.*).

Each of Jean-Marc Jézéquel, Noël Plouzeau, Olivier Barais, Benoit Combemale, Johann Bourcier, Arnaud Blouin, Stéphanie Challita and Mathieu Acher teaches about 250h in these domains for a grand total of about 2000 hours, including several courses at IMT-Atlantique, ENS Rennes and ENSAI Rennes engineering school⁸.

The DiverSE team also hosts several MSc and summer trainees every year.

Responsibilities:

- Olivier Barais is **Deputy Director** of the electronics and computer science teaching department of the University of Rennes 1 (1600 students)
- Olivier Barais is the head of the final year of the Master in Computer Science at the University of Rennes 1
- Noël Plouzeau was the head of the first year of the Master in Computer Science at the University of Rennes 1 since september 2021
- Mathieu Acher will be the head of the first year of the Master in Computer Science at the University of Rennes 1 until August 2025
- Johann Bourcier is head of the Computer Science Department at the ESIR engineering school in Rennes
- Johann Bourcier is co-manager of the Home-Automation option at the ESIR engineering school in Rennes
- Arnaud Blouin is in charge of industrial relationships for the computer science department at INSA Rennes
- Stéphanie Challita is member of the Sustainable Development & Social Responsibility unit at the ESIR engineering school in Rennes

Commitment in Summer Schools:

- Mathieu Acher gave courses to EJCP (Ecole Jeune Chercheur en Programmation), a well-known, national training school for PhD students ([link](#)) (2018, 2019, 2021)

3.5 General Audience Actions

We have led many dissemination actions, we can quickly cite articles in the blog of the newspaper "le monde" but also many dissemination actions in conferences for developers or directly with companies. ▲ Due to space limitation, the complete list of these actions is available [online](#).

3.6 Visibility

3.6.1 Awards

- 2021: [\[144\]](#) Best paper award at SPLC 2021
- 2021: [\[168\]](#) Best paper award at ARES-IWCC 2021
- 2021: [\[144\]](#) Best paper award at SPLC 2021
- 2021: Mathieu Acher Junior member **IUF** ⁹
- 2020: Jean-Marc Jézéquel is the recipient of the [IEEE/ACM International Conference on Model Driven Engineering Languages and Systems \(MODELS\)](#) career award.
- 2020: [\[83\]](#) Best paper award at ICPE 2020

⁸All Professors or Associate Professors have a teaching duty of 192 hours per year, except B. Combemale. (96h) currently on leave (half time) at CNRS, and J-M Jézéquel (96h) when he was dean of IRISA. Djamel and Olivier, as Full-time researchers, have no mandatory teaching duties.

⁹<https://www.iufrance.fr/detail-de-lactualite/247.html>

- 2019: We received the "Data Showcase Award" at the MSR'19 conference (Mining Software Repositories 2019) for the dataset described in the following paper [89] and publicly available on [Zenodo](#).
- 2019: Most Influential Paper (MIP) award at SLE 2019
- 2018: [101] gets the best vision paper at SLE'18.
- 2018: [134] get the best artefact associated to a scientific paper at SLE'18.
- 2018: Winners of the third CNIL-Inria prize for their article [127] "*Beauty and the Beast: diverting modern web browsers to build unique browser fingerprints*", Benoît Baudry, Pierre Laperdrix and Walter Rudametkin.
- 2017: Second position for the ACM Student Research Competition: Thomas Degueule
- 2016: Silver Medal of the CNRS for Jean-Marc Jézéquel

3.6.2 Tutorials and Invited Conferences

Mathieu Acher:

- *Reverse Engineering Language Product Lines from Existing DSL Variants*, David Méndez-Acuña, José Galindo, Benoit Combemale, Arnaud Blouin, Benoit Baudry, at GDR-GPL 2018
- *Re-engineering Software Variability into Software Product Lines*, Tewfik Ziadi, Mathieu Acher, at ASE 2018 ([tutorial](#))
- Tutorials at SPLC 2019 and 2020 about machine learning and SPLs
- Talk at Embedded Linux Conference Europe 2019 ([link](#))

Jean-Marc Jézéquel:

- *Keynote speech at ECMFA 2021*
- *Keynote speech for Performance Modeling workshop associated to ICPE2021*
- *Keynote speech Models@Runtime workshop associated to MODELS2019*
- *Keynote speech for the LIG seminar on the Future of Informatics: "On Turning Domain Knowledge into Tools"*

Djamel E. Khelladi:

- Talk at the *IPA Fall Days* in Wageningen, Netherlands, 2019.
- Invited talk at the GEODES team, University of Montreal, 2019.

Johann Bourcier:

- Talk at the UBS university in Vannes, France.

Benoit Combemale:

- *Smart Modeling: On the Convergence of Scientific and Engineering Models*, Invited talk at Lancaster university, UK (14/11/19).
- *Bringing Intelligence to Sociotechnical IoT Systems: Modeling Opportunities and Challenges*, Keynote at MDDE4IoT'19, DE (15/09/19).
- *Breathe Life Into Your IDE*, Talk at LangDev'19, NL (22/03/19).
- *Model Execution: Past, Present and Future*. Keynote at EXE'18, DK (14/10/18).
- *Modeling For Sustainability - Or How to Make Smart CPS Smarter?.* Keynote at Models@run.time'18, DK (14/10/18), and invited talk at TU Wien, AT (15/05/18)
- *Execution Framework of the GEMOC Studio*. Talk at LangDev'18, NL (08/03/18).
- *From Model (driven) Engineering, to Language (driven) Engineering*, Invited talk at CEA DAM, France.
- *Towards Language-Oriented Modeling*, Invited talk at UQAM (Montreal, Canada).
- *Sound, yet Flexible, Modeling: A Language Engineering Point Of View*, Keynote at FlexMDE'17.
- *Modeling For Sustainability – Or How to Make Smart CPS Smarter?* Invited talk at CWI (Amsterdam, The Netherlands).
- *Model Simulation, Graphical Animation, and Omniscient Debugging with Sirius Animator*. Invited talk at SiriusCon'17.

Benoit Baudry:

- Software technology and DevOps.
- Scientific days of Orange
- Reconciling Diversity and Privacy at the Dagstuhl Seminar on Online Privacy and Web Transparency
- Software diversification as an obfuscation technique, at the International Workshop on Obfuscation: Science, Technology, and Theory

Stéphanie Challita:

- Talk at ENS Rennes, France.

3.6.3 Program Committees, Editorial Boards, Conference Organization and Research Expertise

General Chair

We organized ICPE 2021. Johann Bourcier served as general chair.

We organized MODELS 2016. Benoit Combemale and Benoit Baudry served as general chairs.

In addition to these team-level organizations of these conferences with over 300 participants, we have been PC chair of over 14 conferences and workshops. We have been in the organizing committees of more than 11 international conferences or workshops, and present in more than 100 program committees of conferences in the field over the last years. In addition, the team is present in the editorial boards of leading journals in the field such as SOSYM, IEEE Computer, JSS, JOT, COLA, Springer Journal of Software Quality, STVR Elsevier Journal on Science of Computer Programming. We are present and active in the steering committees of conferences (ACM/IEEE MODELS conference, Chair of the Steering committee of the ACM SIGPLAN conference SLE, SPLC conference, VaMoS conference, ...). Finally, we are regularly called to be part of expert boards of European projects or expert boards for the evaluation of international projects such as ([West Wallenberg](#) in Sweden, Vice President of *InformaticsEurope*, external reviewer for different national research agencies and the European Union (ERC)).

▲ Due to space limitation, the complete list of these actions is available online for [PC chair](#), [PC member](#) and [PB member](#), [Editorial boards](#), [Steering comitee](#), [Research Expertise](#), [Research Administration](#)

From Jan. 2012 to Dec 2020, Jean-Marc Jézéquel has been Director of IRISA (UMR 6074, one of the largest Computer Science public research lab in France, with over 850 members).

3.7 International Collaborations

Through projects but not only, we have many international academic collaborations. These collaborations lead of course to common publications but also participate to the group dynamism by allowing the visit of many international colleagues within the team but also the visit of PhD students within these teams. These collaborations are fully supported by INRIA through two associated teams but also through the recruitment of Gunter on an INRIA international chair for five years.

Inria Associated Teams and Other Formal Collaborations

- ALE

Title: *Agile Language Engineering*

Duration: 2020 - 2023

Coordinator: Benoit Combemale

Partners: *Inria (France)*, CWI (Netherlands)

Inria contact: Benoit Combemale

Summary: ALE will contribute to the field of Software Language Engineering, aiming to provide more agility to both language designers and language users. The main

objective is twofold. First, we aim to help language designers to leverage previous DSL implementation efforts by reusing and combining existing language modules, while automating the deployment of distributed, elastic and collaborative modeling environments. Second, we aim to provide more flexibility to language users by ensuring interoperability between different DSLs, offering live feedback about how the model or program behaves while it is being edited (aka. live programming/modeling), and combining with interactive environments like Jupiter Notebook for literate programming.

- RESIST

Title: *Resilient Software Science (RESIST)*

Duration: 2021 - 2024

Coordinator: Arnaud Gotlieb

Partners: Inria (France), SIMULA (Norway)

Inria contact: Mathieu Acher

Summary: The associated team Resilient Software Science (RESIST) will research the foundations of “*Resilient Software*” *ie.* software systems which can resist failures without significantly degrading their functionality. Over the past years, resilient software systems have become extremely important in various application domains. By combining Inria’s and Simula’s combined expertise in software engineering, resilient software, and AI-based software testing, the RESIST associate team will address the following challenges:

- Utilizing observation data for assessing resilience under varying conditions
- Digital twins for continuous improvement of resilient autonomous/smart systems
- Resilient autonomous systems in the digital and physical world

The goal for RESIST is to explore the science of resilient software by foundational work on advanced a priori testing methods such as metamorphic testing and a posteriori continuous improvements through digital twins.

Informal Collaborations

- Université de Montréal (Canada)
- McGill University (Canada)
- University of Alabama (USA)
- University of Lancaster (UK)
- University of Namur (Belgium)
- Università degli Studi di Cagliari (Italy)
- Università degli Studi dell’Aquila (Italy)
- JKU Linz (Austria)
- TU Wien (Austria)
- Michigan State University (MSU)
- RWTH Aachen University (Germany)
- KTH (Sweden)

Visits of International Scientists


- Nelly Bencomo, Professor at Durham University, visited the team from November to March 2020.
- Gunter Mussbacher, Professor at McGill University, visited the team from January to June 2020.
- Martin Montperrus, Professor at KTH, Sweden, visited the team in December 2019.
- Nicolas Harrand, PhD Student at KTH, Sweden, visited the team in December 2019.
- Paul Temple, postdoc at University de Namur, visited the team in February 2019.
- Thomas Degueule, postdoc at CWI, visited the team in December 2019

- Alfonso Pierantonio, Associate Professor at Università degli Studi dell'Aquila, visited the team in June 2019
- Mark van den Brand, Professor at Eindhoven University of Technology, visited the team in June 2019
- Yves Le Traon, Professor at the University of Luxembourg, visited the team in June and July 2018, 2019, 2021.
- François Fouquet, Junior Researcher at the SnT (Lux), visited the team in March 2018.
- Jordi Cabot, Research Professor at Internet Interdisciplinary Institute, the Research center of the Open University of Catalonia (UOC), SOM Research Lab leader, visited the team in December 2018.
- Erwan Bousse, postdoctoral researcher at TU Wien, Austria, visited the team from January until Aug 2018
- Marcel Heinz, research assistant and PhD student at University of Koblenz-Landau visited the team in Jul 2018
- Yves Le Traon, Professor at the University of Luxembourg, visited the team in June and July 2017.
- Tanja Mayerhofer, Junior Researcher at the TU Wien, visited the team in March 2017.
- François Fouquet, Junior Researcher at the SnT (Lux), visited the team in November 2017

Visits to International Teams

- Pierre JeanJean visited CWI for 1 week in December 2019 in the context of the Associated Team ALE.
- Benoit Combemale made several short visits at CWI in the context of the Associated Team ALE, visited McGill University in June 2019, and visited TU Eindhoven in November 2019.
- Olivier Barais made several short visits at KTH in the context of a collaboration with Prof Monperrus and Prof Baudry.
- Djamel E. Khelladi made a one week research visit in December 2019 to the DIRO laboratory at University of Montreal, Canada.
- Fabien Coulon visited CWI for 1 week in June 2018 in the context of the Associated Team ALE.
- Manuel Leduc visited CWI for 1 week in December 2018 in the context of the Associated Team ALE.
- Benoit Combemale made several short visits at CWI in the context of the Associated Team ALE, and visited TU Eindhoven in November 2018.
- Olivier Barais and Amine Benelallam made several short visits at KTH in the context of a collaboration with Prof Monperrus and Prof Baudry.
- Manuel Leduc visited CWI for 3 weeks in September 2017
- Benoit Combemale visited Professor Jorg Kienzle at McGill University (Canada) for 3 months in 2017; and made several short visits at CWI (The Netherlands)

4 Funding

 Due to space limitations, we do not provide a summary of each project. If required, an extended version of this section is available [online](#) with the project summaries.

National Initiatives

Regional Initiatives

PEC – Pôle d’Excellence Cyber. Coordinator: Université de Rennes 1. Dates: 2016-2019.
Formal and Executable Specification of domain-specific language families. ~ **150 k€**

ANR

MC-Evo₂ ANR JCJC. Coordinator: Djamel Khelladi (CNRS). Dates: 2021-2025 ~ **300 k€**

VaryVary ANR JCJC. Coordinator: Mathieu Acher (UR1). Dates: 2017-2021 ~ **300 k€**
SOPRANO. Coordinator: CEA. CEA, University of Paris-Sud, Inria Rennes, OcamlPro, Adacore. Dates: 2014-2018. ~ **250 k€**

GEMOC. Coordinator: Inria (DIVERSE). Other partners: ENSTA Bretagne, Inria, IRIT, I3S, Obeo, Thales. Dates: 2012-2016. ~ **300 k€**

Gdiv MRSE. Coordinator: B. Baudry, Inria Rennes. Dates: 2014-2016. ~ **100 k€**

IUF

REVARY. Coordinator: Mathieu Acher (UR1). Dates: 2021-2026. ~ **20 k€**

DGA

LangComponent (CYBERDEFENSE). Coordinator: DGA. Partners: DGA MI, INRIA. Dates: 2019-2022. ~ **130 k€**

FPML (CYBERDEFENSE). Coordinator: DGA. Partners: DGA MI, Inria. Dates: 2014-2017. ~ **130 k€**

Cominlabs

PROFILE. Coordinator: Université de Rennes 1. Partners: INRIA, Université de Rennes 2. Dates: 2016-2019. ~ **200 k€**

European Projects

H2020 ICT-10-2016 STAMP. Coordinator: Inria Rennes. Other partners: ATOS, ActiveEon, OW2, TellU, Engineering, XWiki, TU Delft, SINTEF. Dates: 2016-2019 ~ **600 k€**

H2020-ICT-2017-1 TeamPlay. Coordinator Inria Rennes. Other partners: Univ. of Bristol (UK), Univ. of St Andrews (UK), Univ. of Amsterdam (NL), Univ. of Southern Denmark (DK), TUHH (DE), AbsInt (DE), Irida Labs (GR), Thales Alenia space - Espana (ES), Skywatch (DK). Dates: (2018-) 2020-2021 in DiverSE. ~ **620 k€**

H2020-ICT-2019-2 HiPEAC 6. Coordinator Univ. Ghent. Partners: Barcelona Supercomputing Center (ES), Chalmers Univ. (SE), FORTH (GR), Inria Rennes (FR), Univ. of Edinburgh (UK), Univ. of Pisa (IT), RWTH Aachen (DE), CEA (FR), ARM (UK), Thales (FR), ARTEMIS-IA (NL). Dates (2019-) 2020-2023 in DiverSE. ~ **60 k€**

EIT Digital UAV-Retina. Unmanned Aerial Vehicles - Retina. Duration: from 2018-10 to 2019-12. Coordinator: UR1. Other partners: Bright Cape (company from the Netherlands), FBK (Trento University, Italy), JCP Connect (company from France), Tellus Environment (company from France), Fire Department of Ile et Vilaine (France), Fire Department of Trento (Italy). ~ **30 k€**
~ **150 k€**

CEF AQMO. Coordinator: UR1. Airbreizh - Surveillance of Brittany air quality association, branch of the French national air surveillance network, AmpliSIM - SME specialized in pollution numerical simulation, CNRS / IDRIS, GENCI, Neovia, Rennes Métropole, Ryax Technologies. Dates: 2018-2020. ~ **30 k€**
~ **150 k€**

FP7 STREP HEADS. Coordinator: SINTEF. Other partners: Inria, Software AG, ATC, Tellu, eZmonitoring. Dates: 2013-2017.

FP7 FET STREP DIVERSIFY. Coordinator: Inria (DIVERSE). Partners: SINTEF, Université de Rennes 1, Trinity College Dublin, Inria (DiverSE, SPIRALS). Dates: 2013-2016. ~ **500 k€**

ICT COST Action MPM4CPS (IC1404). Chair of the Action: Prof Hans Vangheluwe (BE). Dates: 2014-2018. ~ **50 k€**

Industrial Contracts

Competitvity Clusters/ BGLE / LEOC

Occiware. Coordinator: Open Wide. Partners: Open Wide, ActiveEon SA, CSRT - Cloud Systèmes Réseaux et Télécoms, Institut Mines-Télécom/Télécom SudParis, Inria, Linagora, Obeo, OW2 Consortium, Pôle Numérique, Université Joseph Fourier. Dates: 2014-2018. ~ **300 k€**

CLARITY. Coordinator: Obeo. Other partners: AIRBUS, Airbus Defence and Space, All4tec, ALTRAN Technologies, AREVA, Artal, C.E.S.A.M.E.S., Eclipse Foundation Europe, Inria Sophia Antipolis Méditerranée, PRFC, Scilab Enterprises, Thales Global Services, Thales Alenia Space, Thales Research & Technology, Thales Systèmes Aéroportés, Université de Rennes 1. Dates: 2014-2017. ~ **500 k€**

BGLE2 CONNEXION. Coordinator: EDF. Other partners: Atos WorldGrid, Rolls-Royce Civil Nuclear, Corys TESS, Esterel Technologies, All4Tec, Predict, CEA, Inria, CNRS / CRAN, ENS Cachan, LIG, Telecom ParisTech. Dates: 2012-2016 ~ **300 k€**

Bilateral Contracts with Industry

ADR Nokia. Coordinator: Inria. Dates: 2017-2021. ~ **180 k€**

BCOM. Coordinator: UR1. Dates: 2018-2024. ~ **10 k€**

GLOSE. Partners: Inria/CNRS/Safran. Dates: 2017-2021. ~ **350 k€**

GLOSE Demonstrator. Partners: Inria/Safran. Dates: 2019-2020. ~ **100 k€**

OneShotSoftware. Partners: Inria/Orange. Dates: 2017-2019. ~ **250 k€**

Debug4Science. Partners: Inria/CEA DAM. Dates: 2020-2022. ~ **250 k€**

Agileo. Partners: Inria/Agileo. Dates: 2017-2018 ~ **10 k€**

Kereval. Partners: INSA Rennes/Kereval. Dates: 2019-2020. Front-ends testing in a DevOps context, Romain Lebouc's PhD Cifre project. ~ **20 k€**

Obeo. Partners: Inria/Obéo. Dates: 2017-2020. Web engineering for domain-specific modeling languages, Fabien Coulon's PhD Cifre project. ~ **150 k€**

OKWind. Partners: UR1/OKWind. Dates: 2017-2020. Models@runtime to improve self-consumption of renewable energies, Alexandre Rio's PhD Cifre project. ~ **150 k€**

Orange. Partners: UR1/Orange. Dates: 2016-2019. Modelling and evaluating security of authentication paths, Youssou Ndiaye's PhD Cifre project. ~ **150 k€**

Orange. Partners: UR1/Orange. Dates: 2020-2023. Context aware adaptive authentication, Anne Bumiller's PhD Cifre project. ~ **150 k€**

Keolis. Partners: UR1/Keolis. Dates: 2018-2021. Urban mobility: machine learning for building simulators using large amounts of data, Gauthier LYAN's PhD Cifre project. ~ **150 k€**

FaberNovel. Partners: UR1/FaberNovel. Dates: 2018-2021. Abstractions for linked data and the programmable web, Antoine Cheron's PhD Cifre project. ~ **150 k€**

INRIA Project Labs, Exploratory Research Actions and Technological Development Actions

No support provided by INRIA

Associated teams and other international projects

Inria International Labs

Simula-Inria RESIST. Associated team. <http://gemoc.org/resist/> Title: Resilient Software Science. International Partner: Simula (Normay). Start year: 2021. ~ **20 k€**

IIL CWI-Inria ALE. Associated team. <http://gemoc.org/ale> Title: Agile Language Engineering. International Partner: CWI (Netherlands) with Tijs van der Storm. Start year: 2017. ~ **30 k€**

Collaborations with major European organizations

Vipo Project. Vipo is an innovation project from EIT Digital. This year, we bring our expertise on native cloud architecture and adaptable architectures for this project. ~ **60 k€**

Participation in Other International Programs

The **GEMOC studio** has been sustained through the creation of a Research Consortium at the Eclipse Foundation.

International initiative GEMOC. The GEMOC initiative (cf. <http://www.gemoc.org>) is an open and international initiative launched in 2013 that coordinates research partners worldwide to develop breakthrough software language engineering (SLE) approaches for global software engineering through the use of multiple domain-specific languages.

5 Objectives for the Next Four Years

▲ Due to space limitation, we provide a shorter version of these perspectives in the current report. If reviewers wish to get our vision on the scientific context regarding these challenges, a longer version can be found [online](#). We also try to discuss in this extended version [why we get the required backgrounds, skills and human resources to target these challenges](#).

DiverSE will continue to explore *Software Diversity* over the next period. Leveraging our strong background on Model-Driven Engineering, and our large expertise on several related fields (programming languages, distributed systems, GUI, machine learning, security...), *we explore tools and methods to embrace the inherent diversity in software engineering*, from the stakeholders and underlying tool-supported languages involved in the software system life cycle, to the configuration and evolution space of the modern software systems, and the heterogeneity of the targeted execution platforms. Hence, we organize our research directions over the next period according to three axes (cf. Fig. 3):

- **Axis #1: Software Language Engineering.** We explore the future engineering and scientific environments to support the socio-technical coordination among the various stakeholders involved across modern software system life cycles.
- **Axis #2: Spatio-temporal Variability in Software and Systems.** We explore systematic and automatic approaches to cope with software variability, both in space (software variants) and time (software maintenance and evolution).
- **Axis #3: DevSecOps and Resilience Engineering for Software and Systems.** We explore smart continuous integration and deployment pipelines to ensure the delivery of secure and resilient software systems on heterogeneous execution platforms (cloud, IoT. . .).

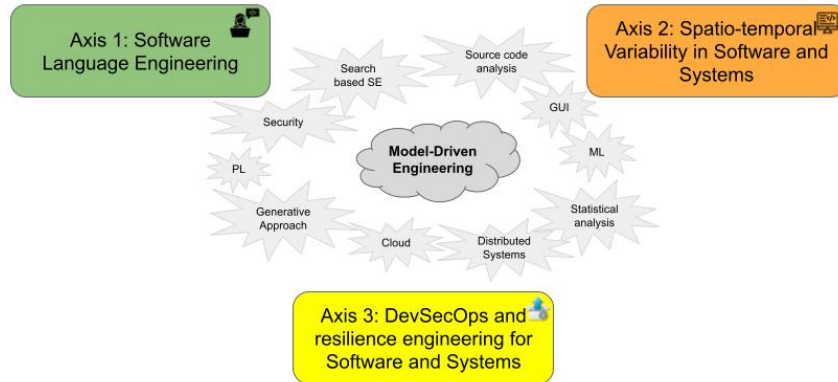


Figure 3: The three future research axes of DiverSE, relying on model driven engineering scientific background and leveraging several related fields

5.1 Axis #1: Software Language Engineering

Overall objective. The disruptive design of new, complex systems requires a high degree of flexibility in the communication between many stakeholders, often limited by the silo-like structure of the organization itself (cf. Conway’s law). To overcome this constraint, modern engineering environments aim to: (i) better manage the necessary exchanges between the different stakeholders; (ii) provide a unique and usable place for information sharing; and (iii) ensure the consistency of the many points of view. Software languages are the key pivot between the *diverse* stakeholders involved, and the software systems they have to implement. Domain-Specific (Modeling) Languages enable stakeholders to address the *diverse* concerns through specific points of view, and their coordinated use is essential to support the socio-technical coordination across the overall software system life cycle. Our perspectives on Software Language Engineering over the next period is presented in Figure 4 and detailed in the following paragraphs.

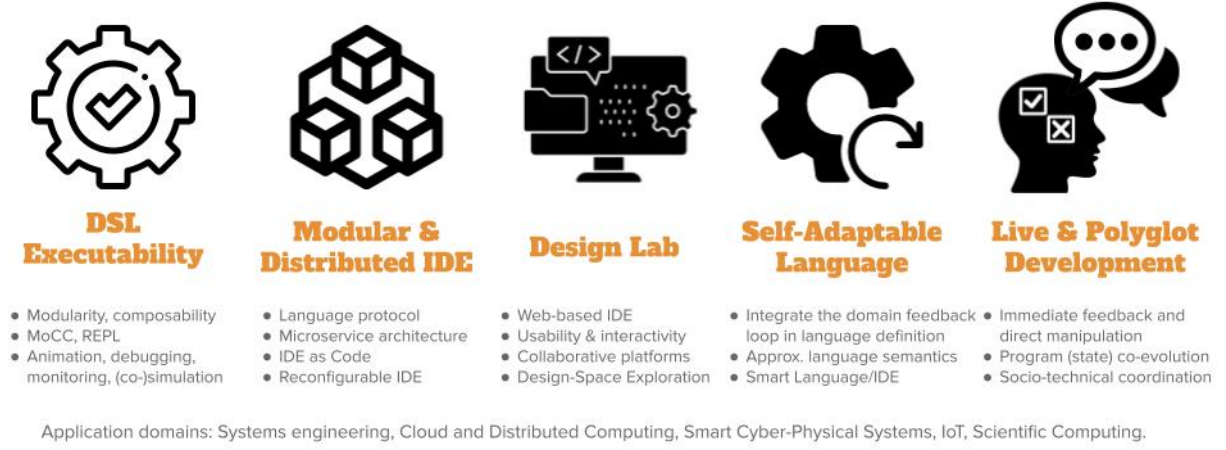


Figure 4: Perspectives on Software Language Engineering (axis #1)

DSL Executability. Providing rich and adequate environments is key to the adoption of domain-specific languages. In particular, we focus on tools that support model and program execution. We explore the foundations to define the required concerns in language specification, and systematic approaches to derive environments (*e.g.*, IDE, notebook, design labs) including debuggers, animators, simulators, loggers, monitors, trade-off analysis, etc.

Modular & Distributed IDE. IDEs are indispensable companions to software languages. They are increasingly turning towards Web-based platforms, heavily relying on cloud infrastructures and forges. Since all language services require different computing capacities and response times (to guarantee a user-friendly experience within the IDE) and use shared resources (*e.g.*, the program), we explore new architectures for their modularization and systematic approaches for their individual deployment and dynamic adaptation within an IDE. To cope with the ever-growing number of programming languages, manufacturers of Integrated Development Environments (IDE) have recently defined protocols as a way to use and share multiple language services in language-agnostic environments. These protocols rely on a proper specification of the services that are commonly found in the tool support of general-purpose languages, and define a fixed set of capabilities to offer in the IDE. However, new languages regularly appear offering unique constructs (*e.g.*, DSLs), and supported by dedicated services to be offered as new capabilities in IDEs. This trend leads to the multiplication of new protocols, hard to combine and possibly incompatible (*e.g.*, overlap, different technological stacks). Beyond the proposition of specific protocols, we will explore an original approach to be able to specify language protocols and to offer IDEs to be configured with such protocol specifications. IDEs went from directly supporting languages to protocols, and we envision the next step: *IDE as code*, where language protocols are created or inferred on demand and serve as support of an adaptation loop taking in charge of the (re)configuration of the IDE.

Design Lab. Web-based and cloud-native IDEs open new opportunities to bridge the gap between the IDE and collaborative platforms, *e.g.*, forges. In the complex world of software systems, we explore new approaches to reduce the distance between the various stakeholders (*e.g.*, systems engineers and all those involved in specialty engineering) and to improve the interactions between them through an adapted tool chain. We aim to improve the usability of development cycles with efficiency, affordance and satisfaction. We also explore new approaches to explore and interact with the design space or other concerns such as software and systems human values or security, and provide facilities for trade-off analysis and decision making.

Live & Polyglot Development. As of today, polyglot development is massively popular and virtually all software systems put multiple languages to use, which not only complexifies their development, but also their evolution and maintenance. Moreover, as software grows more critical in new application domains (e.g., data analytics, health or scientific computing), it is crucial to ease the participation of scientists, decision-makers, and more generally non-software experts. Live programming makes it possible to change a program while it is running, by propagating changes on a program code to its run-time state. This effectively bridges the gulf of evaluation between program writing and program execution: the effects a change has on the running system are immediately visible, and the developer can take immediate action. The challenges at the intersection of polyglot and live programming have received little attention so far, and we envision a language design and implementation approach to specify domain-specific languages and their coordination, and automatically provide interactive domain-specific environments for live and polyglot programming.

Self-Adaptable Language. Over recent years, self-adaptation has become a concern for many software systems that operate in complex and changing environments. At the core of self-adaptation lies a feedback loop and its associated trade-off reasoning, to decide on the best course of action. However, existing software languages do not abstract the development and execution of such feedback loops for self-adaptable systems. Developers have to fall back to ad-hoc solutions to implement self-adaptable systems, often with wide-ranging design implications (e.g., explicit MAPE-K loop). Furthermore, existing software languages do not capitalize on monitored usage data of a language and its modeling environment. This hinders the continuous and automatic evolution of a software language based on feedback loops from the modeling environment and runtime software system. To address the aforementioned issues, we will explore the concept of Self-Adaptable Language (SAL) to abstract the feedback loops at both system and language levels.

5.2 Axis #2: Spatio-temporal Variability in Software and Systems

Overall objective. Leveraging on our longstanding activity on variability management for software product lines and configurable systems covering *diverse* scenarios of use, we will investigate over the next period the impact of such a variability across the *diverse* layers, incl. source code, input/output data, compilation chain, operating systems and underlying execution platforms. We envision a better support and assistance for the configuration and optimisation (e.g., non-functional properties) of software systems according to this deep variability. Moreover, as software systems involve *diverse* artefacts (e.g., APIs, tests, models, scripts, data, cloud services, documentation, deployment descriptors...), we will investigate their continuous co-evolution during the overall lifecycle, including maintenance and evolution. Our perspectives on spatio-temporal variability over the next period is presented in Figure 5 and is detailed in the following paragraphs.

Deep Software Variability. Software systems can be configured to reach specific functional goals and non-functional performance, either statically at compile time or through the choice of command line options at runtime. We observed that considering the software layer only might be a naive approach to tune the performance of the system or to test its functional correctness. In fact, many layers (hardware, operating system, input data, etc.), which are themselves subject to variability, can alter the performances or functionalities of software configurations. We call *deep software variability* the interaction of all variability layers that could modify the behavior or non-functional properties of a software. Deep software variability calls to investigate how to systematically handle cross-layer configuration. The diversification of the different layers is also an opportunity to test the robustness and resilience of the software layer in multiple environments.



Figure 5: Perspectives on Spatio-temporal Variability in Software and Systems (axis #2)

Another interesting challenge is to tune the software for one specific executing environment. In essence, deep software variability questions the generalization of the configuration knowledge.

Continuous Software Evolution. Nowadays, software development has become more and more complex, involving various artefacts, such as APIs, tests, models, scripts, data, cloud services, documentation, etc., and embedding millions of lines of code (LOC). Recent evidence highlights continuous software evolution based on thousands of commits, hundreds of releases, all done by thousands of developers. We focus on the following essential backbone dimensions in software engineering: languages, models, APIs, tests and deployment descriptors, all revolving around software code implementation. We will explore the foundations of a multidimensional and polyglot co-evolution platform, and will provide a better understanding with new empirical evidence and knowledge.

5.3 Axis #3: DevSecOps and Resilience Engineering for Software and Systems

Overall objective. The production and delivery of modern software systems involves the integration of *diverse* dependencies and continuous deployment on *diverse* execution platforms in the form of large distributed socio-technical systems. This leads to new software architectures and programming models, as well as complex supply chains for final delivery to system users. In order to boost cybersecurity, we want to provide strong support to software engineers and IT teams in the development and delivery of secure and resilient software systems, ie. systems able to resist or recover from cyberattacks. Our perspectives on DevSecOps and Resilience Engineering over the next period are presented in Figure 6 and detailed in the following paragraphs.

Secure & Resilient Architecture. Continuous integration and deployment pipelines are processes implementing complex software supply chains. We envision an explicit and early consideration of security properties in such pipelines to help detecting vulnerabilities. In particular, we integrate the security concern in Model-Based System Analysis (MBSA) approaches, and explore guidelines, tools and methods to drive the definition of secure and resilient architectures. We also investigate resilience at runtime through frameworks for autonomic computing and data-centric applications, both for the software systems and the associated deployment descriptors.

Smart CI/CD. Dependencies management, Infrastructure as Code (IaC) and DevOps practices open opportunities to analyze complex supply chains. We aim at providing relevant metrics

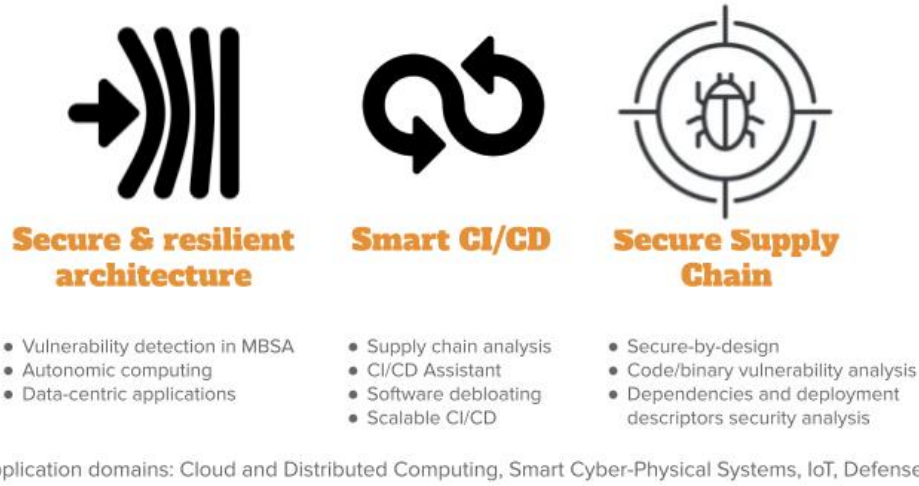


Figure 6: Perspectives on DevSecOps and Resilience Eng. for Software and Systems (axis #3)

to evaluate and ensure the security of such supply chains, advanced assistants to help in specifying corresponding pipelines, and new approaches to optimize them (*e.g.*, software debloating, scalability. . .). We study how supply chains can actively leverage software variability and diversity to increase cybersecurity and resilience.

Secure Supply Chain. In order to produce secure and resilient software systems, we explore new secure-by-design foundations that integrate security concerns as first class entities through a seamless continuum from the design to the continuous integration and deployment. We explore new models, architectures, inter-relations, and static and dynamic analyses that rely on explicitly expressed security concerns to ensure a secure and resilient supply chain. We lead research on automatic vulnerability and malware detection in modern supply chains, considering the various artefacts either as white boxes enabling source code analysis (to avoid accidental vulnerabilities or intentional ones or code poisoning), or as black boxes requiring binary analysis (to find malware or vulnerabilities). We also conduct research activities in dependencies and deployment descriptors security analysis.

▲ If useful to the evaluation, we have provided an [online SWOT analysis](#) by the permanent team members of DiverSE.

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