RESEARCH CENTRE

Inria Paris Centre

2024

ACTIVITY REPORT

Project-Team

PROSECCO

Programming securely with cryptography

DOMAIN

Algorithmics, Programming, Software and Architecture

THEME

Security and Confidentiality

Inria

Contents

Project-Team PROSECCO

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Keywords

Computer sciences and digital sciences

A1.1. – Architectures

A1.1.8. – Security of architectures

A1.2. – Networks

A1.2.8. – Network security

A1.3. – Distributed Systems

A2. – Software

A2.1. – Programming Languages

A2.1.1. – Semantics of programming languages

A2.1.4. – Functional programming

A2.1.7. – Distributed programming

A2.1.11. – Proof languages

A2.2. – Compilation

A2.2.1. – Static analysis

A2.2.5. – Run-time systems

A2.4. – Formal method for verification, reliability, certification

A2.4.2. – Model-checking

A2.4.3. – Proofs

A2.5. – Software engineering

A4. – Security and privacy

A4.3. – Cryptography

A4.3.3. – Cryptographic protocols

A4.5. – Formal methods for security

A4.6. – Authentication

A4.8. – Privacy-enhancing technologies

Other research topics and application domains

B6. – IT and telecom

B6.1. – Software industry

B6.1.1. – Software engineering

B6.3. – Network functions

B6.3.1. – Web

B6.3.2. – Network protocols

B6.4. – Internet of things

B9. – Society and Knowledge

B9.6.2. – Juridical science

B9.10. – Privacy

1 Team members, visitors, external collaborators

Research Scientists

- Bruno Blanchet [Team leader, INRIA, Senior Researcher]
- Aymeric Fromherz [INRIA, ISFP]
- Adrien Koutsos [INRIA, Researcher]
- Sarah Beth Lawsky [INRIA, Senior Researcher, from Oct 2024]
- Denis Merigoux [INRIA, Starting Research Position]

PhD Students

- Alain Delaet-Tixeuil [INRIA]
- Son Ho [INRIA, until Nov 2024]
- Theo Laurent [INRIA, until Oct 2024]
- Antonin Reitz [INRIA]
- Justine Sauvage [INRIA]
- Theo Vignon [ENS PARIS-SACLAY]
- Theophile Wallez [INRIA]

Technical Staff

- Oussama Belbahi [INRIA, Engineer, until Aug 2024]
- Guillaume Boisseau [INRIA, Engineer, from Apr 2024]
- Vincent Botbol [INRIA, Engineer, from Jun 2024]
- Louis Gesbert [INRIA, Engineer, until Aug 2024]
- Paul-Nicolas Madelaine [INRIA, Engineer, until Aug 2024]
- Yoann Prak [INRIA, Engineer, from Mar 2024]

Interns and Apprentices

- Ryan Lahfa [INRIA, Intern, from Mar 2024 until Aug 2024]

Administrative Assistants

- Christelle Guiziou [INRIA]
- Christelle Rosello [INRIA]

External Collaborators

- Marie Alauzen [FONDATION INRIA, from May 2024 until May 2024]
- Benjamin Beurdouche [MOZILLA, until Jan 2024]
- Karthikeyan Bhargavan [CRYSPEN]
- Vincent Cheval [Oxford University]
- Mathieu Durero [DGFIP, until Sep 2024]
- Caroline Flori [DGFIP, until Sep 2024]
- Caroline Fontaine [CNRS]
- Lucas Franceschino [CRYSPEN, from Apr 2024]
- Estelle Hary [RMIT University, from Sep 2024]

2 Overall objectives

2.1 Programming securely with cryptography

In recent years, an increasing amount of sensitive data is being generated, manipulated, and accessed online, from bank accounts to health records. Both national security and individual privacy have come to rely on the security of web-based software applications. But even a single design flaw or implementation bug in an application may be exploited by a malicious criminal to steal, modify, or forge the private records of innocent users. Such *attacks* are becoming increasingly common and now affect millions of users every year.

The risks of deploying insecure software are too great to tolerate anything less than mathematical proof, but applications have become too large for security experts to examine by hand, and automated verification tools do not scale. Today, there is not a single widely-used web application for which we can give a proof of security, even against a small class of attacks. In fact, design and implementation flaws are still found in widely-distributed and thoroughly-vetted security libraries designed and implemented by experts.

Software security is in crisis. A focused research effort is needed if security programming and analysis techniques are to keep up with the rapid development and deployment of security-critical distributed applications based on new cryptographic protocols and secure hardware devices. The goal of our team PROSECCO is to draw upon our expertise in cryptographic protocols and program verification to make decisive contributions in this direction.

Our vision is that, over its lifetime, PROSECCO will contribute to making the use of formal techniques when programming with cryptography as natural as the use of a software debugger. To this end, our long-term goals are to design and implement programming language abstractions, cryptographic models, verification tools, and verified security libraries that developers can use to deploy provably secure distributed applications. Our target applications include cryptographic libraries, network protocol implementations, web applications, and cloud-based web services. In particular, we aim to verify full software applications, including both the cryptographic core and the high-level application code. Furthermore, we aim to verify implementations, not just models. Finally, we aim to account for computational cryptography, not just its symbolic abstraction.

We identify four key focus areas for our research in the short- to medium term.

New programming languages for verified software Building realistic verified applications requires new programming languages that enable the systematic development of efficient software hand-in-hand with their proofs of correctness. We design and implement the programming language F*, in collaboration with Microsoft Research. F* (pronounced F star) is a general-purpose functional programming language with a state-of-the-art type-and-effect system aimed at program verification. Its type system includes polymorphism, dependent types, monadic effects, refinement types, and a weakest precondition calculus.

Together, these features allow expressing precise and compact specifications for programs, including functional correctness and security properties. The F* type-checker aims to prove that programs meet their specifications using a combination of SMT solving and interactive proofs. Programs written in F* can be translated to efficient OCaml, F#, or C for execution. The main ongoing use cases of F* in our group are HACL*, a verified cryptographic library, and DY*, a framework for verifying protocol implementations. Nevertheless, we also consider non-cryptographic security software, for which we also use F* and its extensions, for instance security-enhanced memory allocators, who are often the last line of defense against memory vulnerabilities in critical C and C++ software [33].

We also design two frameworks for the analysis of Rust programs (hacspec and Aeneas), by translation to various theorem provers including F*.

Recently, we extended our work on programming languages to a domain-specific language for implementing law, for instance tax computation, which is also critical as it impacts every citizen. We indeed noticed that much of the infrastructure and methodologies we developed for cryptographic security software can be transferred to other domains in need of high-assurance software. The combination of software engineering and formal methods that we employ at the Prosecco team may thus have a more general field of application beyond cryptographic software.

Symbolic verification of cryptographic applications We aim to develop our own security verification tools for models and implementations of cryptographic protocols and security APIs using symbolic cryptography. Our starting point is the tools we have previously developed: the specialized cryptographic prover ProVerif and the F* verification system via the DY* framework. These tools are already used to verify industrial-strength cryptographic protocol implementations and commercial cryptographic hardware. We plan to extend and combine these approaches to capture more sophisticated attacks on applications consisting of protocols, software, and hardware, as well as to prove symbolic security properties for such composite systems.

Computational verification of cryptographic applications We aim to develop our own cryptographic application verification tools that use the computational model of cryptography. The tools include the computational provers CryptoVerif and Squirrel, and the F* verification system. Working together, we plan to extend these tools to analyze, for the first time, cryptographic protocols, security APIs, and their implementations under fully precise cryptographic assumptions. We also plan to pursue links between tools, in order to use each tool where it is the strongest.

Building provably secure web applications We aim to develop analysis tools and verified libraries to help programmers build provably secure web applications. The tools will include static and dynamic verification tools for client- and server-side JavaScript web applications, their verified deployment within HTML5 websites and browser extensions, as well as type-preserving compilers from high-level applications written in F* to JavaScript. In addition, we plan to model new security APIs in browsers and smartphones and develop the first formal semantics for various HTML5 web standards. We plan to combine these tools and models to analyze the security of multi-party web applications, consisting of clients on browsers and smartphones, and servers in the cloud.

3 Research program

3.1 Symbolic verification of cryptographic applications

Despite decades of experience, designing and implementing cryptographic applications remains dangerously error-prone, even for experts. This is partly because cryptographic security is an inherently hard problem, and partly because automated verification tools require carefully-crafted inputs and are not widely applicable. To take just the example of TLS, a widely-deployed and well-studied cryptographic protocol designed, implemented, and verified by security experts, the lack of a formal proof about all its details has regularly led to the discovery of major attacks (including several in PROSECCO) on both the protocol and its implementations, after many years of unsuspecting use.

As a result, the automated verification for cryptographic applications is an active area of research, with a wide variety of tools being employed for verifying different kinds of applications.

In previous work, we have developed the following approaches:

- ProVerif: a symbolic prover for cryptographic protocol models
- F*: a new language that enables the verification of cryptographic applications

Verifying cryptographic protocols with ProVerif Given a model of a cryptographic protocol, the problem is to verify that an active attacker, possibly with access to some cryptographic keys but unable to guess other secrets, cannot thwart security goals such as authentication and secrecy [56]; it has motivated a serious research effort on the formal analysis of cryptographic protocols, starting with [46] and eventually leading to effective verification tools, such as our tool ProVerif.

To use ProVerif, one encodes a protocol model in a formal language, called the applied pi-calculus, and ProVerif abstracts it to a set of generalized Horn clauses. This abstraction is a small approximation: it just ignores the number of repetitions of each action, so ProVerif is still very precise, more precise than, say, tree automata-based techniques. The price to pay for this precision is that ProVerif does not always terminate; however, it terminates in most cases in practice, and it always terminates on the interesting class of *tagged protocols* [42]. ProVerif can handle a wide variety of cryptographic primitives, defined by rewrite rules or by some equations, and prove a wide variety of security properties: secrecy [39, 29], correspondences (including authentication) [40], and observational equivalences [41]. Observational equivalence means that an adversary cannot distinguish two processes (protocols); equivalences can be used to formalize a wide range of properties, but they are particularly difficult to prove. Even if the class of equivalences that ProVerif can prove is limited to equivalences between processes that differ only by the terms they contain, these equivalences are useful in practice and ProVerif has long been the only tool that proves equivalences for an unbounded number of sessions. (Maude-NPA in 2014 and Tamarin in 2015 adopted ProVerif's approach to proving equivalences.)

Using ProVerif, it is now possible to verify large parts of industrial-strength protocols, such as TLS [3], Signal [53], JFK [30], and Web Services Security [38], against powerful adversaries that can run an unlimited number of protocol sessions, for strong security properties expressed as correspondence queries or equivalence assertions. ProVerif is used by many teams at the international level, and has been used in more than 140 research papers (references).

Verifying cryptographic applications using F* Verifying the implementation of a protocol has traditionally been considered much harder than verifying its model. This is mainly because implementations have to consider real-world details of the protocol, such as message formats [60], that models typically ignore. So even if a protocol has been proved secure in theory, its implementation may be buggy and insecure. However, with recent advances in both program verification and symbolic protocol verification tools, it has become possible to verify fully functional protocol implementations in the symbolic model. One approach is to extract a symbolic protocol model from an implementation and then verify the model, say, using ProVerif. This approach has been quite successful, yielding a verified implementation of TLS in F# [37]. However, the generated models are typically quite large and whole-program symbolic verification does not scale very well.

An alternate approach is to develop a verification method directly for implementation code, using well-known program verification techniques. We design and implement the programming language F* [9], [31, 55], in collaboration with Microsoft Research. F* is an ML-like functional programming language aimed at program verification. Its type system includes polymorphism, dependent types, monadic effects, refinement types, and a weakest precondition calculus. Together, these features allow expressing precise and compact specifications for programs, including functional correctness and security properties. The F* type-checker aims to prove that programs meet their specifications using a combination of SMT solving and interactive proofs. Programs written in F* can be translated to efficient OCaml, F#, or C for execution [59]. The main ongoing use case of F* is building a verified, drop-in replacement for the whole HTTPS stack in Project Everest [35] (a larger collaboration with Microsoft Research). This includes a verified implementation of TLS 1.2 and 1.3 [36] and of the underlying cryptographic primitives [10]. More recently, we have built a new symbolic protocol verification framework in F* called DY* [34] and used it to verify real-world cryptographic protocols like Signal, ACME and Noise.

3.2 Computational verification of cryptographic applications

Proofs done by cryptographers in the computational model are mostly manual. Our goal is to provide computer support to build or verify these proofs. In order to reach this goal, we have designed the automatic tool CryptoVerif, which generates proofs by sequences of games. We already applied it to important protocols such as TLS [3] and Signal [53] but more work is still needed in order to develop this approach, so that it is easier to apply to more protocols.

Another tool we develop, called the Squirrel Prover, uses a symbolic approach called the computationally complete symbolic adversary (CCSA) [32] to verify cryptographic protocols in the computational model. Squirrel is an interactive theorem prover, hence provides less automation than CryptoVerif, but allows the user to guide the proof more easily when complex arguments are needed; and it is better-suited for some protocols, notably for stateful protocols.

A third approach is to directly verify executable cryptographic code by typing. A recent work [48] shows how to use refinement typechecking to prove computational security for protocol implementations. In this method, henceforth referred to as computational F*, typechecking is used as the main step to justify a classic game-hopping proof of computational security. The correctness of this method is based on a probabilistic semantics of F# programs and crucially relies on uses of type abstraction and parametricity to establish strong security properties, such as indistinguishability.

In principle, the three approaches—game-based proofs in CryptoVerif, interactive proofs in Squirrel, and typechecking proofs in F*—are complementary. Understanding how to combine these approaches remains an open and active topic of research. For example, CryptoVerif can generate OCaml implementations from CryptoVerif specifications that have been proved secure [43]. We are currently working on this approach to generate implementations in F*.

3.3 F*: A Higher-Order Effectful Language for Program Verification

F* [9], [31] is a verification system for effectful programs developed collaboratively by Inria and Microsoft Research. It puts together the automation of an SMT-backed deductive verification tool with the expressive power of a proof assistant based on dependent types. After verification, F* programs can be extracted to efficient OCaml, F#, or C code [59]. This enables verifying the functional correctness and security of realistic applications. F*'s type system includes dependent types, monadic effects, refinement types, and a weakest precondition calculus. Together, these features allow expressing precise and compact specifications for programs, including functional correctness and security properties. The F* type-checker aims to prove that programs meet their specifications using a combination of SMT solving and interactive proofs. The main ongoing use case of F* is building a verified, drop-in replacement for the whole HTTPS stack in Project Everest. This includes verified implementations of TLS 1.2 and 1.3 [36] and of the underlying cryptographic primitives [10], [58, 57].

3.4 Analysis of Rust Programs

Rust is a modern programming language that provides both performance and memory safety and is well suited for critical system programming. We develop two frameworks for analyzing Rust programs.

We develop hacspec, a purely functional domain-specific language embedded in Rust for writing succinct executable specifications, in particular for cryptographic algorithms, which can be translated to proof back-ends like F* and Coq.

We also develop Aeneas [50], which leverages Rust's rich region-based type system to eliminate memory reasoning for a large class of Rust programs, as long as they do not rely on interior mutability or unsafe code. Doing so, Aeneas relieves the proof engineer of the burden of memory-based reasoning, allowing them to instead focus on functional properties of their code. Aeneas proposes a new Low-Level Borrow Calculus (LLBC) that captures a large subset of Rust programs, and a translation from LLBC to a pure lambda-calculus, which enables the verification of Rust programs through different theorem provers, such as Lean, Coq, or F*.

3.5 Provably secure web applications

Web applications are fast becoming the dominant programming platform for new software, probably because they offer a quick and easy way for developers to deploy and sell their *app*s to a large number of customers. Third-party web-based apps for Facebook, Apple, and Google, already number in the hundreds of thousands and are likely to grow in number. Many of these applications store and manage private user data, such as health information, credit card data, and GPS locations. To protect this data, applications tend to use an ad hoc combination of cryptographic primitives and protocols. Since designing cryptographic applications is easy to get wrong even for experts, we believe this is an opportune moment to develop security libraries and verification techniques to help web application programmers.

As a typical example, consider commercial password managers, such as LastPass, RoboForm, and 1Password. They are implemented as browser-based web applications that, for a monthly fee, offer to store a user's passwords securely on the web and synchronize them across all of the user's computers and smartphones. The passwords are encrypted using a master password (known only to the user) and stored in the cloud. Hence, no-one except the user should ever be able to read her passwords. When the user visits a web page that has a login form, the password manager asks the user to decrypt her password for this website and automatically fills in the login form. Hence, the user no longer has to remember passwords (except her master password) and all her passwords are available on every computer she uses.

Password managers are available as browser extensions for mainstream browsers such as Firefox, Chrome, and Internet Explorer, and as downloadable apps for Android and Apple phones. So, seen as a distributed application, each password manager application consists of a web service (written in PHP or Java), some number of browser extensions (written in JavaScript), and some smartphone apps (written in Java or Objective C). Each of these components uses a different cryptographic library to encrypt and decrypt password data. How do we verify the correctness of all these components?

We propose three approaches. For client-side web applications and browser extensions written in JavaScript, we propose to build a static and dynamic program analysis framework to verify security invariants. To this end, we have developed two security-oriented type systems for JavaScript, Defensive JavaScript [45] and TS* [62], and used them to guarantee security properties for a number of JavaScript applications. For Android smartphone apps and web services written in Java, we propose to develop annotated JML cryptography libraries that can be used with static analysis tools like ESC/Java to verify the security of application code. For clients and web services written in F# for the .NET platform, we propose to use F* to verify their correctness. We also propose to translate verified F* web applications to JavaScript via a verified compiler that preserves the semantics of F* programs in JavaScript.

3.6 Design and Verification of next-generation protocols: identity, blockchains, and messaging

Building on our work on verifying and re-designing pre-existing protocols like TLS and Web Security in general, with the resources provided by the NEXTLEAP project, we are working on both designing and verifying new protocols in rapidly emerging areas like identity, blockchains, and secure messaging. These are all areas where existing protocols, such as the heavily used OAuth protocol, are in need of considerable re-design in order to maintain privacy and security properties. Other emerging areas, such as blockchains and secure messaging, can have modifications to existing pre-standard proposals or even a complete 'clean slate' design. As shown by Prosecco's work, newer standards, such as IETF OAuth, W3C Web Crypto, and W3C Web Authentication API, can have vulnerabilities fixed before standardization is complete and heavily deployed. We hope that the tools used by Prosecco can shape the design of new protocols even before they are shipped to standards bodies. We are currently contributing to the design and analysis of new extensions to the TLS protocol, such as Encrypted Client Hello, new secure messaging protocol such as IETF Messaging Layer Security (MLS), and to IoT protocols like the IETF Lightweight Authenticated Key Exchange (LAKE).

3.7 Formalizing Law

In France, income tax is computed from taxpayers' individual returns, using an algorithm that is authored, designed and maintained by the French Public Finances Directorate (DGFiP). Owing to the shortcomings

of its custom programming language and the technical limitations of the compiler, the algorithm is proving harder and harder to maintain, relying on ad-hoc behaviors and workarounds to implement the most recent changes in tax law. As an improvement to this infrastructure, we developed Mlang, an open-source compiler toolchain that has been thoroughly validated against the private DGFiP test suite. The DGFiP is now officially transitioning to Mlang for their production system. This line of work has yielded papers at CC 2020 and JFLA, as well as a successful industrial technology transfer from Inria to DGFiP.

Building on the work on Mlang, Prosecco has seen the development of a new domain-specific language, Catala, targeted specifically for legal expert systems. This new domain-specific language has been built in close collaboration with lawyers, and advertised to that community with a number of legal-oriented papers [52]. On the formal methods side, the simple and clean design of the Catala semantics allows for extension into a proper proof platform for the law [44]. Catala has been tested on the real-world French housing benefits [26, 27] and is currently experimented for use at DGFiP.

4 Application domains

4.1 High-Assurance Cryptographic Libraries

Cryptographic libraries implement algorithms for symmetric and asymmetric encryption, digital signatures, message authentication, hashing, and key exchange. Popular libraries like OpenSSL, NSS, and BoringSSL are widely used in web browsers, operating system, and cloud services. We aim to apply our tools and verification techniques to build high-assurance high-performance cryptographic libraries that can be deployed in mainstream software applications. Our flagship project is HACL*, a verified cryptographic library that is written in the F* programming language.

4.2 Design and Analysis of Protocol Standards

Cryptographic protocol standards such as TLS, SSH, IPSec, and Kerberos are the trusted base on which the security of modern distributed systems is built. Our work enables the analysis and verification of such protocols, both in their design and implementation. We participate in standards organizations like the IETF and collaborate with industry groups to help them design and deploy secure protocols. For example, we built and verified models and reference implementations for the well-known TLS 1.3 protocol, using our tools ProVerif and CryptoVerif, before it was standardized at the IETF and contributed to the protocol's final design.

4.3 Web application security

Web applications use a variety of cryptographic techniques to securely store and exchange sensitive data for their users. For example, a website may serve pages over HTTPS, authenticate users with a single sign-on protocol such as OAuth, encrypt user files on the server-side using XML encryption, and deploy client-side cryptographic mechanisms using a JavaScript cryptographic library. The security of these applications depends on the public key infrastructure (X.509 certificates), web browsers' implementation of HTTPS and the same origin policy (SOP), the semantics of JavaScript, HTML5, and their various associated security standards, as well as the correctness of the specific web application code of interest. We build analysis tools to find bugs in all these artifacts and verification tools that can analyze commercial web applications and evaluate their security against sophisticated web-based attacks.

4.4 Formalizing Law

Taxes and social benefits are cornerstones of public policies in developed countries. Concretely, in most places, citizens would fill a form describing their income and family situation, send it to the tax or benefits agency, and then receive or pay the amount the agency has determined based on the information on the form. Determining this amount involves a computation specified by the law, that describes the tax brackets, benefits ceilings, etc. Since this computation is done regularly for a large chunk of the population, it has been computerized for a long time. However, as these aging government IT systems are

becoming harder and harder to maintain, the challenge of accurately computing taxes and benefits in the context of increased public algorithmic scrutiny remains. Reusing our some of our high-assurance software methodology from the domain of cryptography, we have built domain-specific languages and associated tooling to help pairs of programmers and lawyers produce and maintain tax and social benefits IT systems.

5 Social and environmental responsibility

5.1 Footprint of research activities

Our team's work focuses on the design, analysis, and implementation of cryptographic protocols. As such, we are dedicated to improving the security and privacy of all Web users. The output of our research is used, for example, to protect HTTPS connections used daily by millions of Mozilla Firefox users. On the whole, we strive to perform ethical research that improves the digital lives of citizens everywhere.

Our research does not by itself have any environmental impact, but our team does travel to conferences, and we regularly host international visitors, which incurs multiple international flights each year.

6 Highlights of the year

6.1 Awards

- Best tool paper award at ETAPS'24 [20]

7 New software, platforms, open data

7.1 New software

7.1.1 F*

Name: FStar

Keywords: Programming language, Software Verification

Functional Description: F* is a new higher order, effectful programming language (like ML) designed with program verification in mind. Its type system is based on a core that resembles System Fw (hence the name), but is extended with dependent types, refined monadic effects, refinement types, and higher kinds. Together, these features allow expressing precise and compact specifications for programs, including functional correctness properties. The F* type-checker aims to prove that programs meet their specifications using an automated theorem prover (usually Z3) behind the scenes to discharge proof obligations. Programs written in F* can be translated to OCaml, F#, or JavaScript for execution.

URL: https://www.fstar-lang.org/

Contact: Aymeric Fromherz

Participants: Antoine Delignat-Lavaud, Catalin Hritcu, Cedric Fournet, Chantal Keller, Karthikeyan Bhargavan, Pierre-Yves Strub, Aymeric Fromherz

7.1.2 Steel

Name: Steel

Keywords: Program verification, Separation Logic

Functional Description: Steel is a framework for the verification of low-level, concurrent software, and is implemented in the F* dependently-typed programming language. Steel combines a strong, expressive concurrent separation logic to reason about complex concurrency patterns with a high level of automation, mixing custom separation logic decision procedures implemented as F* tactics with generic SMT solving to provide safety and functional correctness guarantees about Steel programs. Steel programs can be translated to executable C code to be integrated in unverified projects.

News of the Year: Development of additional core libraries. Extension of extraction facilities, particularly for concurrency primitives. Application to StarMalloc, a verified, concurrent, hardened memory allocator.

URL: https://github.com/FStarLang/steel

Publications: hal-04104143, hal-02936273, hal-03466397, hal-03626859

Contact: Aymeric Fromherz

Participant: Aymeric Fromherz

Partner: Microsoft

7.1.3 StarMalloc

Keywords: Memory Allocation, Program verification, Separation Logic

Functional Description: StarMalloc is a concurrent, security-oriented, formally verified memory allocator. The functional correctness and memory safety of StarMalloc have been formally established in F*, using the Steel concurrent separation logic. StarMalloc provides all APIs expected from a modern allocator, and was tested with a wide range of applications, including Firefox, Redis, or Z3.

News of the Year: StarMalloc was publicly released, including an entire formally verified development using the Steel concurrent separation logic, as the extracted, executable C code packaged as a standalone, easily deployable artefact. In addition to the APIs and functionalities expected from a modern allocator, the work included the verified development of several security features, including segregated metadata, quarantine, guard pages, and canaries.

StarMalloc was presented at OOPSLA 2024.

URL: https://github.com/Inria-Prosecco/StarMalloc

Publication: hal-04837244

Contact: Aymeric Fromherz

Participants: Aymeric Fromherz, Antonin Reitz

7.1.4 HACL*

Name: High Assurance Cryptography Library

Keywords: Cryptography, Software Verification

Functional Description: HACL* is a formally verified cryptographic library in F*, developed by the Prosecco team at INRIA Paris in collaboration with Microsoft Research, as part of Project Everest.

HACL stands for High-Assurance Cryptographic Library and its design is inspired by discussions at the HACS series of workshops. The goal of this library is to develop verified C reference implementations for popular cryptographic primitives and to verify them for memory safety, functional correctness, and secret independence.

News of the Year: We extended the previously developed streaming API to a wider range of hashes (SHA-1, other variants of SHA-2, SHA-3), which were integrated into CPython, the reference implementation of the Python language. We additionally developed a streaming version of HMAC, supporting all HACL* hashes.

URL: https://github.com/hacl-star/hacl-star

Publications: hal-04301439, hal-03154278, hal-03154275, hal-02294935, hal-01588421

Contact: Aymeric Fromherz

Participants: Karthikeyan Bhargavan, Aymeric Fromherz

7.1.5 DY*

Name: DY*

Keywords: Software Verification, Cryptographic protocol

Functional Description: DY* is a recently proposed formal verification framework for the symbolic security analysis of cryptographic protocol code written in the F* programming language. Unlike automated symbolic provers, DY* accounts for advanced protocol features like unbounded loops and mutable recursive data structures as well as low-level implementation details like protocol state machines and message formats, which are often at the root of real-world attacks. Protocols modeled in DY* can be executed, and hence, tested, and they can even interoperate with real-world counterparts. DY* extends a long line of research on using dependent type systems but takes a fundamentally new approach by explicitly modeling the global trace-based semantics within the framework, hence bridging the gap between trace-based and type-based protocol analyses. With this, one can uniformly, precisely, and soundly model, for the first time using dependent types, long-lived mutable protocol state, equational theories, fine-grained dynamic corruption, and trace-based security properties like forward secrecy and post-compromise security. DY* has been applied to the formal analysis of advanced cryptographic protocols such as Signal, ACME, Noise and MLS.

News of the Year: We developed the tooling around DY* to tackle more complex protocols, and did case studies using this new tooling.

In the past, message formats were written by hand in protocol analysis done with DY*, a process that is both tedious and error-prone. We developed Comparse, a tool to automatically generate messages formats in F*. The generated message formats are usable in DY*, and correspond to the ones defined in protocol specifications.

Cryptographic protocols are often analyzed in isolation. However, they are typically deployed within a stack of protocols, where each layer relies on the security guarantees provided by the protocol layer below it, and in turn provides its own security functionality to the layer above. We extended DY* with a new methodology that allows analysts to modularly analyze each layer in a way that compose to provide security for a protocol stack.

We used DY* to study MLS, a novel secure group messaging protocol. Most cryptographic protocols within the reach of formal analysis are between a fixed number of participants (often two) that exchange a fixed number of messages. MLS gives new challenges for analysts, because it supports group members joining and leaving the group over time, and group members can exchange an unbounded number of messages. We used DY* to study TreeSync, a sub-protocol of MLS that specifies the shared group state, defines group management operations, and ensures consistency, integrity, and authentication for the group state across all members.

URL: https://reprosec.org/

Publications: hal-03178425, hal-03540403, hal-03540824, hal-04255953, hal-04310972

Contact: Theophile Wallez

7.1.6 Hacspec

Keywords: Specification language, Rust

Functional Description: Hacspec is a domain specific language embedded inside Rust geared towards cryptographic specifications. It allows easier communication between formal methods experts and cryptographers that write their implementations in Rust. Hacspec compiles to various proof backends including F* and Coq.

News of the Year: Hacspec was re-implemented entirely and renamed as Hax (https://github.com/hacspec/hax).

Hacspec was aiming at being a specification language for crypto primitives in a DSL embedded in Rust. Hax extends the scope of the project, targeting a large subset of Rust, and translating it to various formal backends (such as Coq, F*, EasyCrypt or ProVerif).

We now call Hacspec the functional subset of Rust that can be used, together with a Hacspec standard library, to write succinct, executable, and verifiable specifications in Rust. These specifications can be translated into formal languages with hax.

URL: https://hacspec.github.io/

Publication: hal-03176482

Contact: Karthikeyan Bhargavan

Partners: Concordium Blockchain Research Center, Université de Porto

7.1.7 Aeneas

Keywords: Rust, Compilers, Program verification

Functional Description: Aeneas is a compilation pipeline for safe Rust programs. Aeneas leverages the Rust type system to compile Rust programs to pure, executable models (i.e., pure, functional versions of the original Rust programs). The key idea behind Aeneas' compilation is that, under the proper restrictions, a Rust function is fully characterized by a forward function, which computes its return value at call site, and a set of backward functions (one per lifetime), which propagate changes back into the environment upon ending lifetimes, thus accounting for side effects. Such forward and backward functions behave similarly to lenses. Relying on theorem provers to state and prove lemmas about those models, it is then possible to enforce guarantees about the original programs. For instance, one can prove panic freedom and functional correctness, but also security guarantees like authentication and confidentiality in the case of cryptographic protocols, and potentially more.

News of the Year: We further extended the subset of Rust supported by Aeneas, including a better support for loops and branches, as well as a support for traits. Additionally, we extended the automation of the Lean backend using metaprogramming to improve the verification experience of using Aeneas.

URL: https://github.com/AeneasVerif/aeneas

Publications: hal-04837250, hal-03931572

Contact: Aymeric Fromherz

Participants: Son Ho, Aymeric Fromherz, Guillaume Boisseau

7.1.8 Charon

Keywords: Rust, Compilers

Functional Description: Charon is a driver which retrieves the Rust compiler output (more precisely, the generated MIR) and translates it to an intermediate language called LLBC (Low Level Borrow Calculus - an "easy-to-use" version of MIR in practice). Charon is meant as a user-friendly, stable interface with the Rust compiler, for the purpose of analyzing Rust programs.

News of the Year: We significantly expanded the subset supported by Charon, including support for unsafe code, associated types, quantified clauses, mutually recursive traits, and many other features. We additionally developed several new static analyses on top of Charon, including a port of the Rudra analyzer, and a analyzer for constant-time programming in cryptographic implementations.

URL: https://github.com/AeneasVerif/charon

Publication: hal-03931572

Contact: Aymeric Fromherz

Participants: Son Ho, Guillaume Boisseau, Aymeric Fromherz, Yoann Prak

7.1.9 mlang

Name: Mlang

Keywords: Compilers, Legality

Functional Description: In France, income tax is computed from taxpayers' individual returns, using an algorithm that is authored, designed and maintained by the French Public Finances Directorate (DGFiP). This algorithm relies on a legacy custom language and compiler originally designed in 1990, which unlike French wine, did not age well with time. Owing to the shortcomings of the input language and the technical limitations of the compiler, the algorithm is proving harder and harder to maintain, relying on ad-hoc behaviors and workarounds to implement the most recent changes in tax law. Competence loss and aging code also mean that the system does not benefit from any modern compiler techniques that would increase confidence in the implementation. We overhaul this infrastructure and present Mlang, an open-source compiler toolchain whose goal is to replace the existing infrastructure. Mlang is based on a reverse-engineered formalization of the DGFiP's system, and has been thoroughly validated against the private DGFiP test suite. As such, Mlang has a formal semantics, eliminates previous handwritten workarounds in C, compiles to modern languages (Python), and enables a variety of instrumentations, providing deep insights about the essence of French income tax computation. The DGFiP is now officially transitioning to Mlang for their production system.

News of the Year: In 2024, the DGFiP completed a first milestone for the integration of Mlang into their IT sytem, as for the first time, the income tax of all French people has been computed thanks to source code compiled with Mlang instead of the legacy DGFiP compiler. Extensions of the M language to soft-code rather than hard-code domain-specific terminology are being tested for productions, and plans to add function calls are underway to finally get rid of the legacy C codebase.

Publications: hal-02320347, hal-03002266

Contact: Denis Merigoux

Participant: Denis Merigoux

Partner: Direction Générale des Finances Publiques (DGFiP)

7.1.10 Catala

Keywords: Domain specific, Programming language, Law

Functional Description: Catala is a domain-specific programming language designed for deriving correct-by-construction implementations from legislative texts. Its specificity is that it allows direct translation from the text of the law using a literate programming style, that aims to foster interdisciplinary dialogue between lawyers and software developers. By enjoying a formal specification and a proof-oriented design, Catala also opens the way for formal verification of programs implementing legislative specifications.

News of the Year: In 2024, the development of Catala is undergoing an industrialization process with three research engineers working on the project, led by Denis Merigoux as the project manager. Beyond a new C89 backend for the compiler that enables integration to legacy backends used in public administrations, the team is now focusing on a new set of front-end features focused on developper tooling as well as algorithmic explainability. Indeed, explaining algorithmic decisions in the context of public service is both useful for the end-user (to know why the decision was issued), and the administration developers that need to debug and fix the system. A design study has begun this year to investigate how to interface the technical log data produced by Catala during execution with user-facing interfaces that satisfy both needs.

URL: https://catala-lang.org/en

Publications: hal-04391612, hal-03712130, hal-03781578, hal-03128248, hal-03159939, hal-02936606, hal-03869335

Contact: Denis Merigoux

Participants: Vincent Botbol, Romain Primet, Denis Merigoux, Louis Gesbert, Aymeric Fromherz, Alain Delaet-Tixeuil, Raphael Monat

Partner: Université Panthéon-Sorbonne

7.1.11 ProVerif

Keywords: Security, Verification, Cryptographic protocol

Functional Description: ProVerif is an automatic security protocol verifier in the symbolic model (so called Dolev-Yao model). In this model, cryptographic primitives are considered as black boxes. This protocol verifier is based on an abstract representation of the protocol by Horn clauses. Its main features are:

It can verify various security properties (secrecy, authentication, process equivalences).

It can handle many different cryptographic primitives, specified as rewrite rules or as equations.

It can handle an unbounded number of sessions of the protocol (even in parallel) and an unbounded message space.

URL: http://proverif.inria.fr/

Publications: hal-03366962, hal-01947972, hal-01423742, hal-01306440, hal-01423760, hal-01102136, hal-01575920, hal-01528752, hal-01575923, hal-01527671, hal-01575861

Contact: Bruno Blanchet

Participants: Bruno Blanchet, Marc Sylvestre, Vincent Cheval

7.1.12 CryptoVerif

Name: Cryptographic protocol verifier in the computational model

Keywords: Security, Verification, Cryptographic protocol

Functional Description: CryptoVerif is an automatic protocol prover sound in the computational model. In this model, messages are bitstrings and the adversary is a polynomial-time probabilistic Turing machine. CryptoVerif can prove secrecy and correspondences, which include in particular authentication. It provides a generic mechanism for specifying the security assumptions on cryptographic primitives, which can handle in particular symmetric encryption, message authentication codes, public-key encryption, signatures, hash functions, and Diffie-Hellman key agreements. It also provides an explicit formula that gives the probability of breaking the protocol as a function of the probability of breaking each primitives, this is the exact security framework.

News of the Year: The main new features of the year are:

1) We improved considerably the translation from CryptoVerif to F*. In particular, it can now translate security properties proved by CryptoVerif into F* axioms. We also support ghost types, for values useful in the CryptoVerif model but not in the F* implementation (e.g. keys of random oracles, which are a modeling artifact).

2) The library of cryptographic primitives has been adapted to support quantum adversaries. In particular, we now have model for KEMs (Key Encapsulation Mechanisms) often used in post-quantum protocols. Moreover, we have a version of the library that contains only primitives with a known post-quantum instantiation, and we have models for primitives without security assumption (useful to model broken primitives, e.g., classical schemes in the presence of a quantum adversary).

These changes are included in CryptoVerif version 2.11 available at `https://cryptoverif.inria.fr`.

URL: `http://cryptoverif.inria.fr/`

Publications: hal-03113251, hal-03471218, hal-04246199, hal-04253820, hal-01947959, hal-01764527, hal-02396640, hal-02100345, hal-04321656, hal-04271666, hal-04577912, tel-01112630, hal-01102382, hal-01528752, hal-01575920, hal-01575861, hal-01575923

Contact: Bruno Blanchet

Participants: Charlie Jacomme, Bruno Blanchet, David Cade, Benjamin Lipp, Pierre-Yves Strub, Christian Doczkal, Pierre Boutry

7.1.13 Squirrel

Name: Squirrel Prover

Keywords: Proof assistant, Cryptographic protocol

Functional Description: Squirrel is an interactive proof assistant dedicated to the formal verification of cryptographic protocols in the computational model. It is based on a higher-order probabilistic logic which supports generic mathematical reasoning as well as cryptographic-specific reasoning.

Concretely, Squirrel allows to specify security protocols in a variant of the applied pi-calculus, and properties of those protocols using its probabilistic logic. Then, these properties are to be proved by the users through tactics. Squirrel supports protocols with unbounded replication and persistent state, and can express both correspondence (e.g. authentication) and indistinguishability properties (e.g. strong secrecy, unlinkability).

News of the Year: Squirrel development continued, with several new features: i) namespaces: objects can now be stored in namespaces, which allows to organize large developments, ii) basic builtin support for integer and string constants, iii) SMT support, and iv), system variables: lemmas and

axioms can now be parameterized by systems, bringing a form of system parametricity where system arguments are inferred during lemma's applications, as for type variables.

In addition, participants of the project published in the ACM SIGLOG newsletter a full presentation of the up to date theory behind the tool.

URL: https://squirrel-prover.github.io/

Publications: hal-04577828, hal-04511718, hal-04579038, hal-03981949, hal-03620358, hal-03172119, hal-03264227

Contact: Adrien Koutsos

Participants: David Baelde, Stephanie Delaune, Clément Herouard, Charlie Jacomme, Adrien Koutsos, Solene Moreau, Thomas Rubiano, Justine Sauvage, Theo Vignon

Partners: IRISA, ENS Rennes

8 New results

8.1 Verification of security protocols in the computational model

Participants: Bruno Blanchet, Aymeric Fromherz, Adrien Koutsos, Justine Sauvage, Théo Vignon.

CryptoVerif We (Bruno Blanchet) continued the development of CryptoVerif, adding new game transformations in order to deal with the dynamic compromise of keys, which allowed us to complete missing proofs of forward secrecy in major previous case studies (TLS 1.3 [3] and WireGuard [54]). We also added game transformations that guess values, a step often used in cryptographic proofs. This work is published at CSF'24 [16].

We (Bruno Blanchet and Charlie Jacomme) showed that CryptoVerif is sound against quantum adversaries. We used this result to obtain the first formal security guarantees over two IETF draft proposals designing post-quantum variants of SSH and TLS. This work is published at CSF'24 [18].

We (Karthikeyan Bhargavan, Bruno Blanchet, Aymeric Fromherz, Benjamin Lipp) developed a translation from CryptoVerif to F*, which allows us to generate running implementations of protocols verified in CryptoVerif. An important addition with respect to a previous translation to OCaml is that we generate F* axioms for security properties proved by CryptoVerif (these axioms can then be used in F* proofs) and lemmas for equations used as assumptions in CryptoVerif (these lemmas are then proved in F*). We (Bruno Blanchet, Pierre Boutry, Christian Dockzal, Benjamin Grégoire, and Pierre-Yves Strub) also developed a translation from the security assumptions used in CryptoVerif to EasyCrypt. Indeed, the security assumptions in CryptoVerif are often stated in a way that differs from the usual cryptographic assumptions. This translation allows us to prove the CryptoVerif assumptions from more standard or lower-level assumptions in EasyCrypt. This work is published at CSF'24 [17]. All these developments are included in CryptoVerif 2.11.

Squirrel Squirrel is an interactive theorem prover dedicated to the verification of cryptographic protocols in the computational model. The Squirrel prover, first introduced in [2], encodes cryptographic protocols and their properties into a pure probabilistic logic, and supports generic as well as cryptographic-specific reasoning.

Squirrel's logic operates in the asymptotic security framework, This is a standard and established framework in the cryptographic community, which allows for simpler proofs by abstracting away irrelevant details, such as the probability of asymptotically negligible events, or small changes in the running times of the involved parties. Concrete security [61] is another established framework which requires the user to prove explicit bounds on the winning probability of the adversary. Because of the increased burden it puts on the user, we did not initially target this framework. Nonetheless, it has advantages: it

allows to obtain precise security bounds, and it is required for some particular cryptographic reasoning steps (e.g. to handle uniformity in hybrid arguments [47]). Recently, we showed how to extend Squirrel's logic to concrete security by adding new security predicate and a corresponding proof system. Further, we designed a novel proof-transformation technique which shows that a large class of asymptotic security proofs can be automatically rewritten into concrete security proofs, while improving their security bounds. This work, which is of a theoretical nature, has been published at CSF'24 [14].

The CCSA logics and its implementation in SQUIRREL come with cryptographic axioms whose soundness derives from the security of standard cryptographic games, e.g. PRF, EUF, IND-CCA. Unfortunately, these axioms are complex to design and implement; so far, these tasks were manual, ad hoc and error-prone. Further, adding a new axiom required to modify the SQUIRREL tool itself, puting this task out-of-reach of the standard users. We solved these issues by providing a formal and systematic method for deriving axioms from cryptographic games. Our method relies on synthesizing an adversary against some cryptographic game, through the notion of bi-deduction. Concretely, we defined a rich notion of bi-deduction, justified how to use it to derive cryptographic axioms, provide a proof system for bi-deduction, and an automatic proof-search method. This work has been published at CSF'24 [15] and included in the main version of SQUIRREL.

8.2 High-Assurance High-Performance Crypto

Participants: Aymeric Fromherz, Son Ho.

Since 2017, we maintain and distribute the HACL* verified cryptographic library, which is currently deployed in many mainstream software applications and high-performance networking stacks including Mozilla Firefox, Linux Kernel, WireGuard VPN, Microsoft WinQuic, Tezos Blockchain, and ElectionGuard.

In ICFP 2023, we (Son Ho, Aymeric Fromherz, and Jonathan Protzenko) published a paper [25], on using advanced features of F*, such as verified meta-programming, to build generic streaming APIs for cryptographic constructions in HACL*. Building upon this work, we applied this year our methodology to a variety of streaming APIs, particularly targeting hashing algorithms. In collaboration with Python developers, we (Aymeric Fromherz and Jonathan Protzenko) then integrated several of these constructions into CPython's hashlib.

8.3 Verification of cryptographic protocol implementations in the symbolic model: the DY* framework

Participants: Karthikeyan Bhargavan, Théophile Wallez.

In collaboration with colleagues at the University of Stuttgart and IIT Gandhinagar, we developed DY*, a new formal verification framework for the symbolic security analysis of cryptographic protocol code written in the F* programming language. Unlike automated symbolic provers, our framework accounts for advanced protocol features like unbounded loops and mutable recursive data structures, as well as low-level implementation details like protocol state machines and message formats, which are often at the root of real-world attacks.

This year, we (Théophile Wallez) did a consequent redesign of DY* which allows us to separate security proofs from protocol specifications, helping us to make the latter more readable and auditable. We revamped an internal construction (security labels) to make them more expressive, hence allowing to prove more security properties of cryptographic protocols. We designed a new way to construct security invariants (a key ingredient of security proofs), allowing to build them modularly, and allowing both vertical and horizontal composition of security invariants.

8.4 Extensions to F*

Participants: Aymeric Fromherz, Antonin Reitz.

Since 2010, our group contributes to the design, implementation, and application of the F* programming language and verification work.

Since 2020, we work on a framework, called Steel [49], based on concurrent separation logic, for developing and proving concurrent programs embedded in F*. Steel proposes a new formalism of Hoare quintuples which involve both separation logic and first-order logic, and enable an efficient verification condition generation and proof discharge using a combination of tactics and SMT solving.

This year, we (Antonin Reitz and Aymeric Fromherz) presented and released StarMalloc, a verified, hardened, concurrent memory allocator. StarMalloc is entirely developed in Steel, supports concurrent allocations, and provides all APIs expected from modern allocators, including those specified in the C standard, those present in the GNU C library, as well as POSIX extensions. As part of an experimental evaluation, we demonstrated the applicability of StarMalloc on a wide-range of real-world applications, such as the Redis key-value store, the Lean compiler, the Z3 SMT solver, or the Firefox web browser. We presented StarMalloc at OOPSLA 2024 [13].

8.5 Formalizing and Implementing Law

Participants: Alain Delaët-Tixeuil, Aymeric Fromherz, Louis Gesbert, Denis Merigoux, Vincent Botbol, Romain Primet.

Since 2021, we develop a new domain-specific language, Catala, targeted specifically for legal expert systems. This language has been built in close collaboration with lawyers, and advertised to that community with a number of legal-oriented papers [52, 51]. On the formal methods side, the simple and clean design of the Catala semantics [8] allows for extension into a proper proof platform for the law [44].

This year, we (Aymeric Fromherz and Denis Merigoux, in collaboration with Raphael Monat) particularly studied the semantics of date arithmetic, which commonly occurs in legal computations, e.g., to determine whether a citizen is eligible to social benefits depending on their birth date. We proposed a formal semantics for date arithmetic, which precisely characterizes when ambiguities due to date rounding occur. We mechanized this semantics in the F* proof assistant, and proved several theorems about our semantics. We finally developed a novel static analysis based on abstract interpretation to automatically detect possible ambiguities, and applied this analysis to existing Catala codebases. This work was presented at ESOP 2024 [20], and received a Best Tool Paper Award.

2024 has also been an important year for the technology transfer of Catala into French public institutions. A first year-long real-scale experiment at the DGFiP ended in July, with very positive results as around 5% of the computation for French income tax has been correctly modeled and tested in Catala, including difficult mechanisms like pro-rated deficits and deductions. At the end of 2024 though, the DGFiP still had not decided what would be the follow-up to this experimentation in their institution, in the midst of political turmoil and hard budgetary times in the French administration. On the other hand, the positive results of the DGFiP experiment prompted the CNAF to include Catala as one of the technology tested in a large-scale study about the future of CRISTAL, the software computing a large number of social benefits. At the time when this report is drafted, early resultats from the CNAF experiment also seem to confirm the technical adequacy of Catala to model the clauses for social benefits computation, as well as the technical feasability to integrate Catala-generated software artifacts into a larger information system such as the CNAF's.

8.6 Verification of Rust programs: Aeneas and hacspec

Participants: Son Ho, Aymeric Fromherz, Guillaume Boisseau, Yoann Prak, Karthikeyan Bhargavan, Lucas Franceschino.

In collaboration with Jonathan Protzenko and Aymeric Fromherz, Son Ho developed a new verification toolchain for Rust programs called Aeneas. Aeneas leverages Rust's rich region-based type system to eliminate memory reasoning for a large class of Rust programs, as long as they do not rely on interior mutability or unsafe code. Doing so, Aeneas relieves the proof engineer of the burden of memory-based reasoning, allowing them to instead focus on functional properties of their code. Aeneas proposes a new Low-Level Borrow Calculus (LLBC) that captures a large subset of Rust programs, and a translation from LLBC to a pure lambda-calculus, which enables the verification of Rust programs through different theorem provers. Initial versions of Aeneas were presented at ICFP 2022 [50] and RW 23 [28].

This year, we focused on formalizing Aeneas' symbolic execution, which is the core component of the framework. In particular, we showed that Aeneas' symbolic execution implements a borrow-checker for the subset of Rust supported, and that successfully borrow-checked programs do not get stuck when executing. To do so, we provided a formal semantics for the symbolic execution, dubbed LLBC#, and proved simulation relations between LLBC# and LLBC, as well as between LLBC and a C-like, low-level language. In doing so, we also extended Aeneas' capabilities to support loops and joins. This work was presented at ICFP 2024 [12].

Karthikeyan Bhargavan and Lucas Franceschino worked on the development of hacspec, a purely functional subset of Rust that is used to specify and verify cryptographic algorithms. Specifications in hacspec can be compiled to F* and Coq, and an EasyCrypt backend is being developed. The hacspec framework has been used to specify a large set of cryptographic algorithms and is being used as part of new standardization efforts.

9 Bilateral contracts and grants with industry

Cybercampus CIRCUS funding Creating Innovative and Robust Cryptographic Solutions.

Participants: Aymeric Fromherz.

- Partners: Inria Paris/EPI Prosecco, Cryspen.
- Prosecco PI: Aymeric Fromherz
- Abstract: This project aims to build a new integrated development and verification environment (IDVE) called Circus that is targeted at software developers and security architects. The main partner for this technical transfer is Cryspen, a new company spun off from Prosecco that aims to create innovative cryptographic solutions. The Circus IDVE targets the Rust language, and consists of several tools developed at Prosecco, such as hacspec and Aeneas, while relying on well-established verification tools for the verification of safety, correctness, and security properties about critical software.

10 Partnerships and cooperations

10.1 International initiatives

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

VeriSPro

Title: Verifying Security Properties of Group Messaging Protocols

Duration: 2022 ->

Coordinator: Abhishek Bichhawat (abhishek.b@iitgn.ac.in)

Partners:

- IIT Gandhinagar (Inde)

Inria contact: Aymeric Fromherz

Summary: Modern instant messaging systems allow multiple parties to communicate with each other in pairs and in groups. The security of these conversations depends on complex cryptographic protocols with subtle security guarantees. These protocols allow the addition and deletion of members, as well as the exchange of confidential and authentic messages between (current) members. It is difficult to be confident that these protocols and their implementations are correct. Formal mechanized security analysis of protocols has been widely accepted as a necessary step for designing robust cryptographic protocols but has not been previously used to analyze group messaging. This proposal focuses on formally verifying security properties (like forward secrecy and post-compromise security) of group messaging protocols. We propose to extend DY*, a symbolic verification tool, to build a generic formal framework to model group-messaging protocols. We will model various group messaging protocols and verify different security properties ranging from authentication of peers in a group to the confidentiality of messages exchanged between the peers. Finally, we will use our generic framework to empirically compare of performance of those protocols.

10.2 International research visitors

10.2.1 Visits of international scientists

Inria International Chair

Participants: Sarah Lawsky.

We received the visit of Sarah Lawsky, professor at Northwestern Pritzker School of Law, as part of the Inria International Chair program, from October 7 to December 4. She worked on Catala, our language for formalizing law, in particular applying it to international examples such as the American tax-code and the US-France tax treaty.

Other international visits to the team

Sanjiva Prasad

Status: Professor

Institution of origin: IIT Delhi

Country: India

Dates: May 25 to June 8, 2024

Context of the visit: Extensions of DY* to group messaging protocols

Mobility program/type of mobility: Associated team VeriSPro

Abhishek Bichhawat

Status: Assistant Professor

Institution of origin: IIT Gandhinagar

Country: India

Dates: May 25 to June 8, 2024

Context of the visit: Extensions of DY* to group messaging protocols

Mobility program/type of mobility: Associated team VeriSPro

10.3 National initiatives

10.3.1 PEPR

PEPR Cybersecurity SVP

Participants: Bruno Blanchet (local PI), Aymeric Fromherz, Adrien Koutsos, Justine Sauvage, Théo Vignon.

Title: SVP – Verification of Security Protocols

Other partners: IRISA/team SPICY, Inria Nancy/EPI PESTO, Inria Sophia Antipolis/EPI STAMP, LMP - ENS Paris-Saclay/team INSPIRE.

Duration: July 2022–June 2028

Coordinator: Stéphanie Delaune, IRISA/Équipe SPICY

Summary: The SVP project aims at enabling the analysis of protocols (either already deployed or in the design phase) at the level of abstract specifications, both symbolic and computational, as well as implementations. We want to develop techniques and tools allowing the implementation of solutions whose security will not be questioned in a cyclic way. To achieve this challenge, we (i) develop new functionalities in existing tools to allow the analysis of more and more complex protocols ; (ii) build bridges between the different existing proof techniques and associated tools in order to take advantage of the strengths of each of them ; (iii) validate the techniques and tools developed within this project on widely deployed protocols and on more recent, fast-growing applications, such as Internet voting.

PEPR Quantic PQ-TLS

Participants: Oussama Belbahi, Bruno Blanchet (local PI), Aymeric Fromherz.

Title: PQ-TLS: Post-quantum padlock for web browsers

Other partners: Université Rennes I, Université de Limoges, Université de Rouen, Université de Bordeaux, Université de Saint-Quentin-en-Yvelines, Université de Saint-Étienne, ENS de Lyon, Inria (EPI Grace, Caramba, Cosmiq, Cascade), CEA LETI, CNRS (IMB, IRISA, LABSTICC, LHC, LIP, LIX, LMV, LORIA, XLIM), ANSSI, CryptoNext, PQShield SAS, CryptoExperts

Duration: January 2022–December 2028

Coordinator: Pierre Alain-Fouque, Université Rennes I

Summary: The famous “padlock” appearing in browsers when one visits websites whose address is preceded by “https” relies on cryptographic primitives that would not withstand a quantum computer. This integrated project aims to develop in 5 years post-quantum primitives in a prototype of “post-quantum lock” that will be implemented in an open source browser. The evolution of cryptographic standards has already started, the choice of new primitives will be made quickly, and the transition will be made in the next few years. The objective is to play a driving role in this evolution and to make sure that the French actors of post-quantum cryptography, already strongly involved, are able to influence the cryptographic standards of the decades to come.

10.3.2 ANR

HOPR

Participants: Adrien Koutsos (local PI) .

Title: HOPR – Higher-Order Probabilistic and resource-aware Reasoning

Other partners: CNRS (IRISA), Inria (Sophia Antipolis/EPI SPLITS, Lille/EPC SyCoMoRES)

Duration: January 2025–December 2028

Coordinator: Patrick Baillot, Inria Lille

Participants: Adrien Koutsos

Summary: The HOPR project aims at: i) developing formal logical framework allowing for the **combination of higher-order computation with both probabilities and resources**; and ii), the application of these novel frameworks to improve practical verification tools for cryptography (notably SQUIRREL and Easycrypt). Combining higher-order computation, probabilistic reasoning and representation of complexity-bounded computation is inherently difficult because these features have non-trivial interactions. Nonetheless, we believe that doing so will bring greater *scalability* (developing proofs for larger systems), *expressivity* (expressing properties against new classes of attackers) and *extensibility* (allowing existing tools to handle new notions of privacy) to verification tools.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

Member of the organizing committees

- Adrien Koutsos was a co-organizer for the annual meeting of the GT-MFS 2024 (French working group on formal methods for security).
- Aymeric Fromherz co-organized the ICFP Programming Contest 2024.

11.1.2 Scientific events: selection

Member of the conference program committees

- Bruno Blanchet: PC member for HCVS'24, CCS'24, USENIX Security'25, CSF' 25.
- Aymeric Fromherz: PC member for CSF' 25, USENIX Security'24 and USENIX Security'25.
- Adrien Koutsos: PC member for CCS'24, CCS'25, CSF'25.
- Denis Merigoux: PC member for the Gilles Kahn prize 2023, JFLA'25.

11.1.3 Journal

Member of the editorial boards

- Adrien Koutsos: Editor of the ACM Transactions on Privacy and Security (ACM TOPS).
- Denis Merigoux: Editor of the Journal of Cross-disciplinary Research in Computational Law (CRCL).

11.1.4 Invited talks

- Adrien Koutsos: invited talk “Mechanizing and Automating Cryptographic Arguments”, May 2024, ETH Zurich, ProTeCS workshop (associated to EuroCrypt’24).
- Aymeric Fromherz: invited panel member, "Research, Grad School, Community - Let’s Chat", Milan, September 2024, PLMW workshop (associated to ICFP 24)
- Aymeric Fromherz: Demi-heure de Science, "Améliorer la fiabilité d’implémentations cryptographiques optimisées à l’aide de vérification formelle", December 2024, Inria Paris.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Master: Bruno Blanchet, Proofs of security protocols, 36h equivalent TD, master M2 MPRI, université Paris VII
- Master: Adrien Koutsos, Proofs of security protocols, 18h equivalent TD, master M2 MPRI, université Paris VII
- Master: Aymeric Fromherz, Proofs of security protocols, 18h equivalent TD, master M2 MPRI, université Paris VII
- Summer school: Bruno Blanchet, CryptoVerif: Mechanizing Game-Based Proofs of Security Protocols, XXIII International School on Foundations of Security Analysis and Design (FOSAD’24), 6h.

11.2.2 Supervision

- PhD in progress: Théo Vignon, Exploring the limits of the CCSA approach to computational security, since September 2023, supervised by Caroline Fontaine, Guillaume Scerri, and Adrien Koutsos.
- PhD in progress: Alain Delaët-Tixeuil, Interactive verification for programs deriving from legal specifications, since September 2022, supervised by Sandrine Blazy and Denis Merigoux.
- PhD in progress: Antonin Reitz, A Methodology for Programming and Verifying Secure Systems, since November 2022, supervised by Bruno Blanchet and Aymeric Fromherz.
- PhD in progress: Justine Sauvage, Games and Logic for the Verification of Cryptographic Protocols, since September 2022, supervised by Bruno Blanchet, David Baelde, and Adrien Koutsos.
- PhD in progress: Théophile Wallez, Verification of Cryptographic Protocols, since September 2021, supervised by Karthikeyan Bhargavan, Bruno Blanchet, and Jonathan Protzenko.
- PhD in progress: Théo Laurent, Dependent types and subtyping, since July 2020, supervised by David Delahaye, Bruno Blanchet, and Kenji Maillard.
- PhD in progress: Pierre Goutagny, PhD student in EPC SyCoMoRES (Inria, University of Lille, and CNRS) on Automated Verification of Catala Programs, since September 2024, supervised by Patrick Baillot, Raphael Monat, and Aymeric Fromherz.
- PhD defended: Son Ho, Verification of Rust Programs, defended on December 9, 2024, supervised by Karthikeyan Bhargavan, Bruno Blanchet, and Jonathan Protzenko [21].
- M2 internship: Ryan Lahfa, Formal verification of Rust programs with Aeneas and Lean, supervised by Aymeric Fromherz.

11.2.3 Juries

- Bruno Blanchet: reviewer of Maïwenn Racouchot’s PhD thesis, Université de Lorraine.

12 Scientific production

12.1 Major publications

[1] M. Abadi, B. Blanchet and C. Fournet. 'The Applied Pi Calculus: Mobile Values, New Names, and Secure Communication'. In: *Journal of the ACM (JACM)* 65.1 (Oct. 2017), pp. 1–103. DOI: 10.1145/3127586. URL: https://hal.inria.fr/hal-01636616.

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[9] N. Swamy, C. Hriţcu, C. Keller, A. Rastogi, A. Delignat-Lavaud, S. Forest, K. Bhargavan, C. Fournet, P.-Y. Strub, M. Kohlweiss, J. K. Zinzindohoué and S. Zanella-Béguelin. 'Dependent Types and Multi-Monadic Effects in F*'. In: *43rd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL)*. ACM, Jan. 2016, pp. 256–270. URL: https://hal.inria.fr/hal-01265793 (cit. on pp. 6, 7).

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12.2 Publications of the year

International journals

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International peer-reviewed conferences

[14] D. Baelde, C. Fontaine, A. Koutsos, G. Scerri and T. Vignon. 'A Probabilistic Logic for Concrete Security'. In: *2024 IEEE 37th Computer Security Foundations Symposium (CSF)*. CSF 2024 - 37th IEEE Computer Security Foundations Symposium. Enschede, Netherlands: IEEE Computer Society, 2024, pp. 324–339. URL: https://hal.science/hal-04577828 (cit. on p. 18).

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[20] ***Best Paper***
R. Monat, A. Fromherz and D. Merigoux. 'Formalizing Date Arithmetic and Statically Detecting Ambiguities for the Law'. In: *Lecture Notes in Computer Science*. ESOP 2024 - 33rd European Symposium on Programming. Vol. 14577. Lecture Notes in Computer Science. Luxembourg City, Luxembourg: Springer Nature Switzerland, 5th Apr. 2024, pp. 421–450. DOI: 10.1007/978-3-031-57267-8_16. URL: https://hal.science/hal-04536403 (cit. on pp. 10, 19).

Doctoral dissertations and habilitation theses

[21] S. Ho. 'Formal Verification of Rust Programs by Functional Translation'. Université PSL (Paris Sciences & Lettres), 9th Dec. 2024. URL: https://theses.hal.science/tel-05004605 (cit. on p. 24).

Reports & preprints

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Software

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12.3 Cited publications

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