Explainable Verification (Public)

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Abstract

Summary in English: The cost of software failure is staggering. A rigorous approach to improving software quality and reducing bugs is sound program analysis based on abstract interpretation. In this project, we will push the state of the art in the abstract interpretation of multi-threaded programs written in complex mainstream programming languages, such as C. The goal of this project is to increase trust in the verification process through explainability. To trust the analysis specification, we will explain its mathematical foundations and essence; to increase trust in the implementation, we will enable tools to explain their results to other tools for validation; to gain the trust of the end users, we will enable tools to also explain their reasoning in human-readable form. To achieve these goals, the project will combine research in sound program analysis with compositional methods from programming language and category theory.

Summary in Estonian: Tarkvaratõrgete põhjustatud kulu on jahmatav. Range viis tarkvara kvaliteedi parandamiseks ning vigade vähendamiseks on korrektne programmianalüüs abstraktse interpretatsiooni abil. Selles projektis parendame abstraktse interpretatsiooni meetodeid keerulistes peavoolu programmeerimiskeeltes, nagu C, kirjutatud mitmelõimeliste programmide analüüsimiseks. Selle projekti eesmärk on verifitseerimisprotsessi usaldusväärsust seletatavuse kaudu suurendada. Analüüsi spetsifikatsiooni usaldamiseks selgitame selle matemaatilisi aluseid ja olemust; analüsaatori usalduse suurendamiseks võimaldame selle tulemuste selgitamist eesmärgiga, et need teiste tööriistade poolt valideerida; lõppkasutajate usalduse võitmiseks võimaldame analüsaatoritel selgitada oma arutluskäiku ka inimloetaval kujul. Nende eesmärkide saavutamiseks ühendab projekt korrektse programmianalüüsi meetodite uurimise kompositsiooniliste meetoditega programmeerimiskeelte- ja kategooriateooriast.

1 Scientific Background

The cost of software failure is staggering, estimated to be $2.41 trillion in 2022 [68]. Moving fast is tempting, but in the long run, quality assurance pays off [117]. An exemplary tale is that of the European avionics giant, Airbus, which is now reaping the rewards of a focus on quality [7]. Airbus is a leading backer [34, 70, 107] of a rigorous approach to software verification called **abstract interpretation** [35], which provides a unified view of **static program analysis**. When abstractly interpreting a program, one evaluates it using *abstract values* that over-approximate the set of *concrete values* that the program may see in actual execution. The theory spurred the development of various *numeric abstract domains*, capturing relationships between program variables [36, 79], and practical tools, such as Astreé [37], capable of verifying control software in Airbus aircraft [70].

Given the success of abstract interpretation in providing strong safety guarantees, the wider adoption of rigorous verification approaches would "dramatically reduce software vulnerability" [26]. Thus, one may wonder why abstract interpretation is not more widely used beyond the safety-critical domain? Unlike most source code analysis tools, abstract interpreters aim to be **sound** [105], meaning that they aim to never miss a bug (*no false negatives*). This means a sound tool must assume the system can behave in any possible way that has not been ruled out. This tends to result in *many false positives* that overwhelm users. Sound tools, thus, require much more sophisticated and computationally expensive analyses. Applying these methods on real-world programs is currently difficult, as they require human intervention and deep specialist knowledge [40]. As the sophistication increases, there is also an increased risk of the tool itself being incorrect. This is particularly true for *generative artificial intelligence*. While it can potentially help improving code [123], an industry white paper reports disconcerting trends for maintainability [52] and Stack Overflow, a popular Q&A site for programmers, has banned its use [108]. The impact of these tools remains to be seen, but it is clear that as code becomes easier to generate, it is increasingly important to precisely specify, clearly understand, and thoroughly verify its correctness.

In this project, we will respond to these concerns through a *mixture of foundational and applied research*, building upon and combining the individual *expertise of each project member and partner*, so as to be able to successfully answer our **main research question**:

How can we increase trust in the results of automated software verification tools, while at the same time making rigorous verification approaches more easily usable for developers?

Before explaining how we will answer this question, we first review the relevant **scientific background**.

Abstract interpretation based program analyses have traditionally been specified using **constraint systems** [35, 106] over abstract domains. The system speaks about *unknowns* representing points of interest in the program, while *constraints* formalise how the abstract values stored at each unknown are related. The system is solved by a *fixpoint solver* [45, 53, 62, 71]. If the domain is a lattice of finite height, the solver will eventually converge to a solution; otherwise, solving can be accelerated by applying **widening** and **narrowing** to deal with non-Noetherian analysis domains [9, 10, 14]

In the presence of function calls, the unknowns are **context-dependent** and the system is potentially infinite. The solver then starts with an initial query to some unknown of interest and explores the constraint system only as much as needed to determine the value of the queried unknown, computing a *partial solution* of the system. Challenges arise when one targets **multi-threaded** programs written in complex mainstream languages, such as C, as reasoning about the correctness of one thread is now dependent on how other threads behave. Considering all interleavings of threads does not scale; instead, **thread-modular** variants of abstract interpretation have been developed [78, 80, 82, 111, 112], including by us [100, 101], in which one can analyse each thread in isolation, and then combine the results for a global analysis. In loc. cit. we develop a "local" trace semantics to better justify the analyses in the challenging, but common setting of shared-variable concurrency. When threads communicate via shared globals, this results in "non-local" flows in the analysis—while we analyse a thread based on its local control flow, it can be influenced by other threads, and vice versa, through the globals. To deal with non-local flow in the computation of partial solutions of an infinite system over non-Noetherian domains, our analyses will be based on **side-effecting constraint systems** [12, 120].

In such systems, if an expression e constrains an unknown, the evaluation of e can also affect other unknowns using side-effects.

To increase trust in tools built on such methods and to make them more easily usable, the common theme in the proposed research is **explainability**—by *better explaining their mathematical foundations and essence*, by *better explaining the verification results of one tool to other tools*, and by *better explaining the verification results to developers.*

For **explaining the mathematical foundations and essence** of such tools, we will build on methods from **programming language** and **category theory**. These fields are inherently *compositional*, meaning that definitions, properties, and their proofs are naturally built from smaller building blocks, with larger ones naturally following from smaller ones. They provide us a useful starting point for explaining the foundations of sound program analysis tools in a mathematically natural and compositional way. In particular, we will explore existing and develop new **type-and-effect systems** [17, 66, 74, 124] as a compositional typing-based means to structure programs' correctness specifications and the abstractions they use, and their correctness proofs. This approach is particularly suitable because both the programs we verify (concurrent, multi-threaded) and the methods we use (side-effecting constraints and effectful solvers) contain side-effects. To relate such typing-based foundations back to the (concrete) semantics of the programs in question and the respective program analyses, we will employ the **(graded) monadic denotational semantics** of effectful programs [66, 75, 76, 81, 88]. We describe other, more specific related methods in individual work packages.

As automated verification of real-world programs remains a demanding challenge, the research community has turned to **cooperative verification**, where different tools focus on what they do best, and exchange information and **explain their results to other tools** to jointly verify programs [22, 23]. This is particularly important with the advent of large language models, allowing powerful but heuristic tools to generate invariants that can be validated by sound logic-based tools. The challenge in allowing tools to communicate is to find a common language for expressing invariants and counterexamples, as different tools might represent, e.g., the heap and thread scheduling information differently. It is, however, possible to speak of such things indirectly, e.g., if invariants involve pointer variables or by introducing ghost variables to represent the scheduler state. **Witnesses** are such method-agnostic proof objects that help other analysers validate analysis results. They are used at the International Contest on Software Verification, SV-COMP, to validate counter-examples [21, 24], and correctness invariants [25], though only for single-threaded programs.

Regarding **explaining program analysis results to users**, when a tool identifies a flaw in the program, it is possible to produce a counterexample execution trace that is useful for debugging the program and understanding the flaw. For instance, this has been critical to the success of model checking [32]. In contrast, when a sound analyser verifies the absence of errors in a program, it does not produce an equivalent human-readable artefact to explain this verdict. The challenge we shall be working on in this project is to expose how an automated verifier proves that a property holds along *all* possible executions of the program in a way that is interpretable by humans [16].

The project's findings will be implemented in and evaluated using Goblint [122], a sound program analysis tool actively developed by our group, in collaboration with TU Munich.

2 Objectives, hypotheses, methods

As stated above, our **goal** is to *increase trust in the results of automated software verification tools*, while at the same time *making rigorous verification approaches more easily usable* for developers. Our **hypothesis** is that we can achieve this, if:

O1 We understand the mathematical foundations underpinning the tools and can compositionally prove their correctness.

O2 We can produce machine-checkable witnesses that certify the program analysis results and have other tools validate them.

O3 We can explain the results of the tools to developers in an understandable way.

To achieve these **objectives**, we will combine the full range of programming language research and associated mathematical methods through a synthesis of theoretical, applied, and impact-focussed research, structured into the following **work packages (WPs)**.

WP1: Mathematical Foundations

While sound static program analysis has been successful, reasoning about its correctness is often non-compositional and cumbersome [83, 100], the mathematical foundations are at times unclear, and some aspects have not been studied in depth at all. We will address these concerns using a variety of compositional methods from programming language and category theory.

WP1.1 Modular Proofs for Thread-Modular Analyses, via Effects When justifying thread-modular analyses, the traditional approach is to use induction on the steps of an interleaving semantics [80]. As Mukherjee et al. [83] point out, this makes the proofs tedious as every abstraction needs to repeat history-based reasoning—instead they advocate for a thread-modular concrete semantics that can be conveniently abstracted, at the price of sacrificing precision. We have recently presented a thread-local concrete semantics that is more precise, but again requires history-based arguments for each abstraction [100]. We will investigate methods and abstractions to achieve modularity for such proofs, while retaining precision. Motivated by their compositional nature, and by the recent work on using single-threaded programs' analysis solutions for effect-typing [59], we will investigate the use of type-and-effect systems for compositionally structuring thread-modular analyses of concurrent programs, including their correctness proofs. We will also draw inspiration from Ahman et al's [6] work on typing-based reasoning about monotonic properties of state, where the main application is exactly to simplify history-based arguments. We then aim to connect all this back to the concrete thread-local semantics and thread-modular analysis using a monadic semantics.

WP1.2 Foundations of Side-Effecting Constraint Systems To better understand the practical applications and usefulness of side-effecting constraint systems, we will investigate their more precise mathematical essence. While at the moment solvers pass the meanings of side-effects to constraints as functional arguments, we will explore expressing such constraints more abstractly in terms monads and related structures [15, 72, 81]. We expect that this will shed new light both to the generation of such constraints from control-flow graphs (as a monadic semantics) and to the solvers of such constraints (in terms of their mathematical foundations and how to better structure their correctness proofs). A promising direction is to represent the constraints using monads for algebraic

effects [18, 88], because then effect handlers [2, 64, 89] would allow us to supply and update the meanings of side-effects compositionally. By distinguishing between programs', constraints', and solvers' effects, it will be easier to compositionally reason about allowed interactions and rule out unwanted ones. We will also investigate side-effecting constraint systems' algebraic essence, regarding in which categories and for which functors are their solutions (initial) algebras for [15], and how both their monadic nature and their partial solution aspect fit into the algebraic picture. A good understanding of their algebraic nature will offer new insights into compositional proof methods, such as deriving corresponding (co)induction principles [48, 54].

WP1.3 Interactive and Incremental Analysis Past work on incremental abstract interpretation has focussed either on single-threaded programs [109, 110] or accumulative approaches for shared global variables [104]. These methods were designed for analysing large codebases incrementally. Our more recent efforts [43] have concentrated on the incremental nature of interactive program analysis. When editing in an IDE, shared globals that over-approximate the entire editing history are insufficient. Since shared variables tend to influence significant portions of the program, restarting all globals results in only marginal performance gains over a complete re-analysis. For a holistic approach, we will investigate both the mathematical foundations and the algorithmics involved in achieving truly interactive and incremental analysis. We will build on the results of WP1.1-1.2 on a monadic, effectful understanding of program analysis to explore combining them with mathematical methods for modelling programs' interactive and incremental behaviour, such as update monads [3] and lenses [4], and more generally the areas of bidirected transformations [1] and optics [87]. For algorithms, we will explore ways to limit the reach of recomputation by restarted globals and will implement other algorithmic improvements to constraint system solving, on the one hand, guided by the mathematics we develop, and on the other hand, guiding the kinds of mathematics we need to develop to be able to reason about such algorithms [50, 51].

WP2: Automated Software Verification Algorithms

Engineering a sound static program analysis tool is a complex task. This includes already just defining and implementing the algorithms, before even thinking of verifying their correctness. Our goal is to make progress on both fronts. We will investigate symbolic algorithms for more precise and scalable thread-modular analysis, we will develop novel means for different verifiers to cooperate, and we will also work on machine-checked proofs.

WP2.1 Verified Solvers for Sound Program Analysis. Making program analysis tools more dependable is an active area of research, e.g., novel testing methods have been developed for [29, 67] and there have also been attempts at developing fully certified analysers [19, 27, 33, 39, 46, 63]. However, none of these target mainstream languages in their full complexity, and support side-effecting constraint systems and the techniques (like widening and narrowing) used in our tools. Instead, inspired by these works, and building on Seidl's work [56] on the formal verification of simplified versions of our solvers, we will work towards a better and formally verified feature-complete solver (e.g., based on the Top-Down [14, 71] or RLD solver [13, 103]) that also accommodates side-effecting constraints and other techniques crucial in our tools. As extrinsic, direct-style formal proofs quickly become as complex as pen-and-paper ones, if not worse, then using the monadic insights from WP1 we will explore solver verification in an intrinsic style, e.g., based on Ahman's past work on Dijkstra monads [5, 74] in F* [115], in which specifications

are expressed compositionally in a type-and-effect system and proofs are intertwined with code. We will explore using mainstream proof assistants, such as Coq [114] or Agda [113], and ones tailored for verifying effectful programs, such as F*. Franceschino et al. [46] present an abstract interpreter for a toy language in F*, and highlight the benefits of the intrinsic style.

WP2.2: Precise and Effective Thread-Modular Abstractions. In the past, we have made progress on thread-modular analysis [100, 101] and Goblint's performance on SV-COMP benchmarks is impressive. When analysing real-world C programs, however, we fail to capture which thread actions may happen in parallel when they rely on heap-allocated control structures to synchronise their actions. Based on studying the failures of SV-COMP tools, we have formed the working hypothesis that symbolic reasoning techniques, analogous to how we reason symbolically about heap-based locking patterns [102], could be adapted to reason about time-based patterns. We will develop both the required theory, and implement and evaluate these ideas in Goblint. We also expect to benefit from the theoretical developments in WP1.1, not only in order to better conduct the proofs, but also to guide the design of novel abstractions and algorithms. We will also investigate if we can practically apply the use of graded effects as an additional check on the analysis [59].

WP2.3 Witnesses and Cooperative Verification. Currently, no witness format exists for exchanging multi-threaded correctness invariants. Expressing invariants over all possible interleavings is challenging, and thus thread-modular or rely-guarantee invariants are more suitable. We have shown how to integrate invariants involving pointer variables [98]. We have also shared ideas on how witnesses may reason about thread scheduling [93], and researchers working on the Ultimate Automizer tool have extended our proposal to support ghost variables [20]. We are collaborating with them (together with TU Munich) to develop methods for expressing and validating more refined multi-threaded invariants. The use of ghost variables provides a complete proof method, but when the scheduler state is encoded in the program state, this does not provide sufficient structure for a thread-modular analyser to benefit from the witness. We will be able to show that exchange is possible in principle, but for exchange of more intricate correctness arguments, we will benefit from work, in WP1.1, on the essence of thread-modular reasoning. We will also work on witnesses for data race detection: we aim to extend the witness format towards exchanging information about multiple property violations, similar to the standardised analysis results interchange format, SARIF [44], to build CoOpeRace, a specialised instance of the cooperative verification platform CoVeriTeam [22] for race detection.

WP3: Explainable Verification in Practice

The usability aspects of sound static analysers deserve more research attention, as empirical studies suggest that poor explainability of analysis results is a serious obstacle preventing the wider adoption of static analysis tools [30, 42, 60, 85, 116].

WP3.1: Explainable Abstract Interpretation. Apinis and Vojdani [11] provide a framework for explaining the results of abstract interpretation using the general approach to deriving meta-analyses developed by Cousot et al. [38]. Using our approach has the benefit that the explanations are guaranteed to be semantically consistent with the result of the analysis. Meta-analyses in general are an active area of research, with a potentially

high impact on the usability of verification tools. E.g., there are meta-analyses that focus on quantifying precision loss [28, 49]. We will contribute to this research as follows. First, the framework of Apinis and Vojdani [11] was instantiated for a single-threaded analysis. We will extend it to explain thread-modular analysis [100, 101] in terms of underlying rely-guarantee reasoning [61]. Another important direction is to use our symbolic representation of the analysis computation, and identify which slices of the systems are relevant to being able to compute a given property. Then, we can investigate whether applying results from integer and linear optimisation can provide human-readable explanations, analogous to how generalised Farkas certificates [31] are used in probabilistic model checking [47].

WP3.2: Practical Research on Verification User Interfaces. Here we aim to enhance the usability of sound static analysis for developers by seamlessly integrating it into their workflow. While WP1.3 develops the algorithms for interactive analysis, there is also the need to research how verification tools should be presented in IDEs. Holter has started the development of an IDE integration, GobPie [57], for Goblint, using MagPie Bridge [73]. This allows program analysis results to be presented in the IDE, and updated as the program is edited, but it gives a static view of the analysis. Recent years have seen work on how to display analysis results in a more dynamic manner, giving a similar experience to conventional debuggers: VisuFlow [90], Multiverse Debugging [86, 118], and Symbolic Debugging [65]. We will explore how abstract reachability graphs of Saan [92] can be traversed through the Debug Adapter Protocol [77], so as to experience context-sensitive analysis through a debugger interface. We will then extend this method to provide a meaningful debugging experience for our thread-modular analyses. This can be further improved by the methods for extracting symbolic explanations from WP3.1. Finally, we will devise methods to pinpoint the root causes of the warnings generated by thread-modular analysis. We can draw inspiration from methods for single-threaded programs, such as dependency-based alarm diagnosis [91], the repositioning approach [84], and responsibility analysis [41].

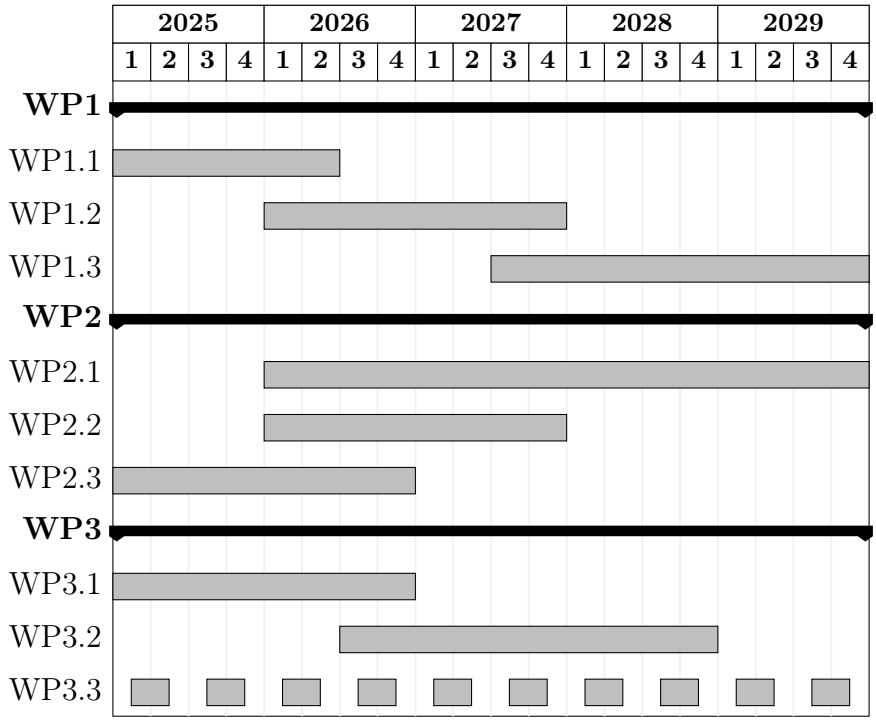
WP3.3: Improving Benchmarking and Evaluation Processes. To assess what tools can do in practice and incentivise the continuous improvement of these tools, the community has established verification contests [8]. We regularly compete at SV-COMP with the Goblint analyser, evaluating our approach [94], auto-tuning [95], memory safety analyses [96] and witness validation [97]. As we integrate the novel methods we develop in this project into our analyser, we will continue to compete annually in SV-COMP. We will also investigate how to evaluate tools on more realistic benchmarks, and aim to improve the benchmarking process that the community uses. In particular, how to extract representative kernels of verification challenges from real-world programs that can be submitted to SV-COMP, and recognising the importance of circling back to the original program [69], how to continuously evaluate research-based tools in real-world scenarios. Starting with the concurrent programs suite of Hong and Ryu [58], we aim to set up a framework—The Continuous Race—for live benchmarking data race verifiers on *real-world* programs using continuous integration workflows. There are interesting research challenges in designing an evaluation process that adapts the ideas from SV-COMP to a more realistic setting using the cooperative race detection artefacts from WP2.3.

Work plan: WP (co-)leads, Gantt chart, WP interactions

We assign the following **leads, co-leads, and partners** to individual work packages:

	Description	**Leads & Project Partners** & Co-leads
WP1	**Mathematical Foundations**	**Ahman & Kammar**
WP1.1	Modular Proofs	Nester
WP1.2	Foundations of Side-Effecting	Apinis
WP1.3	Incremental Analysis	Saan
WP2	**Verification Algorithms**	**Apinis & Seidl**
WP2.1	Verified Solvers	Ahman
WP2.2	Thread-Modular Reasoning	Vojdani
WP2.3	Witness Validation	Saan
WP3	**Explainable Verification**	**Vojdani & Lam**
WP3.1	Explainable Analysis	Apinis
WP3.2	Verification UIs	Holter
WP3.3	Evaluation	Saan

The **durations and order of work packages** is visualised in the following **Gantt chart**:



We also foresee a significant amount of **interaction between work packages**. First, *later work packages will naturally learn from and build on the results of earlier ones.* But in addition, there will also be *interaction between overlapping work packages.* In particular, the results of WP1 will be used to inform and guide the more applied work in WP2,3, whereas WP2,3 will give additional input to WP1 regarding problems faced in practice. This in turn means that WP1.1 and WP1.2 could be revisited even after their planned durations, or WP1.3 started earlier, based on the

findings and encountered challenges in the more applied WP2-3. In addition, all WPs, especially the more applied ones, will feed into the evaluation and benchmarking WP3.3, whose duration in the Gantt chart is partitioned to coincide with submitting to and participating at SV-COMPs.

3 Impact

3.1 Expected Results, Scientific Impact, and Future Research

The potential scientific impact of the project is significant, as the project addresses a critical and timely issue in software development in enhancing software quality and reducing costly errors [26, 117]. As a result, we will have better algorithms and more dependable tools for program analysis (WP2, WP3). We will have better understanding of our approaches mathematical foundations (WP1), and our tools will be easier for users to adopt (WP3).

Scientific impact. We will advance sound program analysis research by refining abstractions of concurrent programs and verifying real-world applications. If successful, the project's novel focus on usability and explainability in program analysis will result in the popularization of sound static analysis techniques. The project's other major focus on mathematical foundations will explain the essence of such analyses and why we can trust them, including how to best prove them correct, and it will connect sound program analysis to other major computer science areas, namely, type systems and category theory.

International collaboration & knowledge transfer. Our demonstrated collaboration with TU Munich and our active participation at SV-COMP has allowed the young researchers in our group to exchange knowledge with the elite of the European verification community. We will continue it in this project. Our dedication to contributing real-world benchmarks to SV-COMP will encourage other researchers and tool developers to address real-world software issues. The collaboration with our project partners, in particular the planned visits in both directions, will give our group access to invaluable know-how and expertise in their respective fields. Furthermore, Ohad Kammar has offered to deliver a lecture course on quasi-Borel spaces and the semantics of (statistical) probabilistic programming during his planned visits to Tartu. We will advertise this course also outside our group and institution, so that the whole Estonian scientific community could benefit from it at a time when probabilistic methods are becoming increasingly important with the emergence of ever more artificial intelligence tools.

Applicability. The open-source nature of our tools facilitates knowledge sharing and adoption by the broader community. We adhere to high software engineering standards, using continuous integration to ensure that the tools build, enabling others to use them. As a result, people are beginning to use Goblint as a baseline representative of the state-of-the-art in sound static race detection, e.g., an application of Goblint for ensuring the safety of OCaml bindings to C libraries was presented by Edwin Török of XenServer [119].

3.2 Importance of the project outside academia

By investigating the foundations and developing tools for improving software quality, including focusing on how to make it easier for developers to adopt such tools, the project will contribute towards a more reliable digital infrastructure. We have already emphasized that software errors have staggering economic costs. They also have serious societal implications because weaknesses in software can be exploited by hackers. As over two-thirds of vulnerabilities are due to programming errors, sound static analysis is important for improving cyber security [26].

Implementation plan and technology transfer. In Munich, the PI participated in the Artemis IA project MBAT [55], working on the analysis of automotive code [99]. Taking into account the lessons learned, our current proposal is designed with clear pathways from theoretical results to practical tools, with dedicated work packages for overcoming

the obstacles to industrial application, including explainability (WP3.1) and usability (WP3.2). Meanwhile, in WP3.3, we aim to improve the community processes for the evaluation of tools such that the transfer gap between research and industry is shortened. Beyond that, we will be proactive in engaging with industry partners. The PI presented Goblint at the Industry Day of the CHESS project [121], and given resources, we could participate and help organise industry events in Estonia. This also includes active participation in Meetups of the Estonian IT community, with interest in functional programming, where partnerships can be formed. We also plan to participate in one larger EU project with industrial partners. As a first attempt at this, Dietmar Pfahl, the professor of software systems here at Tartu, included us in a proposal for Horizon Cluster 4, where we will consider the use of AI for the heuristic parts of the unassuming process.

Teaching plan and knowledge transfer. The project will also ensure the preservation and enable the growth of programming language and software verification research and expertise at the University of Tartu and in Estonia more broadly. Our anticipated results and the knowledge we acquire and develop will have a direct impact on the education of future IT professionals in Estonia. Our group's involvement in mandatory undergraduate programming courses ensures that a considerable proportion of students entering the IT workforce will be equipped with the knowledge and skills acquired through our research. This will lead to better-trained professionals capable of developing high-quality software, and it will allow them to then also bring these good practices to their future employers, which include both private companies and government institutions. We will also release open source tools and develop educational resources based on our research to equip users with the necessary knowledge for effectively using analysers and understanding program correctness principles.

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