RESEARCH STATEMENT

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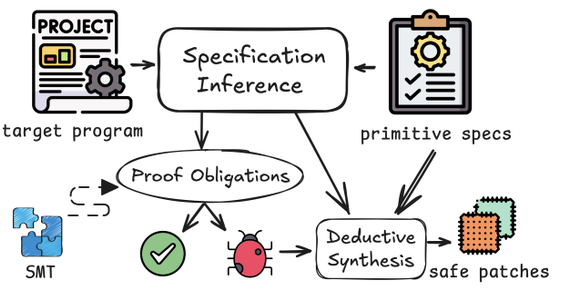
My research focuses on Programming Languages and Formal Methods, emphasizing Specification, Compositional Verification, and Logic – particularly temporal and separation logic. In general, "compositional verification" refers to the capability of proving a program's correctness or incorrectness in a modular manner, which decomposes the reasoning about a whole, complex program into an analysis of its simpler, reusable components.

I am especially interested in leveraging formal reasoning techniques for establishing program correctness, bug detection, and automated program repair. These methods complement traditional approaches like testing, which often fail to provide comprehensive coverage of all possible scenarios. For the future of program analysis and software reasoning, I believe the focus should be on the following key areas: (I) Advanced Logic for Specification: Developing sophisticated logical frameworks to enhance specification capabilities; (II) Practical Inference Mechanisms: Creating effective methods for generating modular specifications; (III) Automated Formal Verification Framework: Streamlining the process of proving software correctness through automation; and (IV) Scalability: Ensuring that systems support automated, incremental reasoning and promote the reuse of effort.

Past Research and Ongoing Work

Modular & Expressive Temporal Verification. The predominant technique in temporal verification, automata-based model checking, has several limitations: it requires a manual modelling phase, is constrained by bounded analysis due to the lack of symbolic reasoning, and is restricted in expressiveness by finite-state automata. To address these challenges and combine the advantages of both modularity and automation, I explore a more precise and extensive solution for temporal verification. More specifically, it deploys Hoare-style forward verifiers as the front end and term rewriting systems (TRSs) as the back end. Forward verifiers compute the actual temporal behaviours from the source code based on the formally defined execution semantics of the target languages. TRSs are decision procedures inspired by Antimirov and Mosses's algorithm [13] but solving the language inclusions between expressive *symbolic linear temporal properties*, which are used to represent program behaviours and specifications. In this approach, the temporal constraints can be dependent on program variables, allowing for more expressive and precise verification. My PhD thesis demonstrates the applications of this framework across various domains, including event-based reactive systems [1], synchronous languages like Esterel [2], user-defined algebraic effects and handlers [3], real-time systems [4], and preemptive asynchronous programs [5].



Program Repair guided by Linear Temporal Properties. As a postdoctoral fellow, I expanded my research into bug detection and automated program repair. To enable a more flexible specification style on top of the classic pre/post-conditions, our recent work [6] allows users to write a "future condition" to modularly express the expected behaviours after function calls, which provides the guideline for automatically detecting and repairing temporal bugs. Our tool, ProveNFix, is configured with 17 pre-defined specifications for primitive APIs and detects 515 bugs from over 1 million lines of code spanning ten real-world C projects. The benefit of our approach is that a small set of properties can be specified once and used to analyze a large number of programs. The novel analysis contributes to an efficient repair strategy that generates patches symbolically. This work has been rec-

ognized with a **Distinguished Paper Award at FSE 2024** for its advancements in automated *specification inference* and its broad applicability across diverse types of bugs. The powerful specification inference techniques help understand complex stateful implementations, for which often no formal specification may be available in real life - partially addressing a long-standing issue in software engineering.

Staged Specification Logic. I am broadly interested in language features such as higher-order imperative programming, which promotes reusable code and design patterns, and algebraic effects, which provide a monadic framework for handling non-determinism and probabilistic programming. To verify such essential language features, one inherent limitation of existing specification mechanisms is their reliance on only two stages: an initial stage to denote the precondition at the start of the method and a final stage to capture the postcondition.

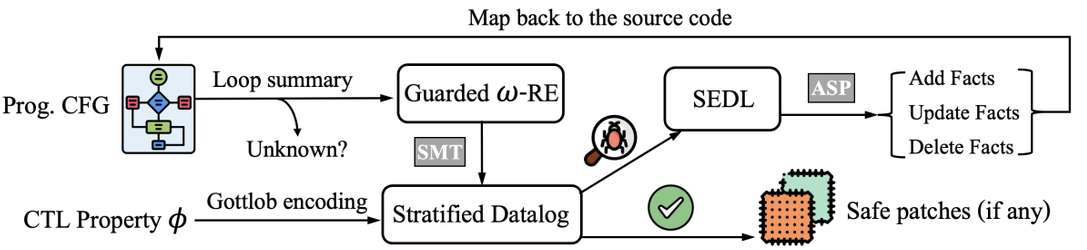
Bi-Abduction

$$\frac{?A * P \vdash Q * ?F}{\texttt{ens P; req Q} \rightarrow \texttt{req A; ens F}}$$

Such two-stage specifications force abstract properties to be imposed on unknown function parameters, leading to less precise specifications for higher-order methods. To overcome this limitation, we introduce a novel extension to Hoare logic that supports multiple staged specifications with a separation logic instantiation. Multiple stages allow the behaviour of unknown function-type parameters/unhandled effects to be captured abstractly as uninterpreted relations. Staged logic is supported by a set of *bi-abduction*-based normalization, which allows a mostly automated specifications inference, requiring only auxiliary lemmas to be provided. Our "staged specification" has proven effective in verifying higher-order imperative programs [7], heap-manipulating algebraic effects and handlers [8], and shift/reset control operators [9].

Incorrectness Proofs for Object-Oriented Programs. In addition to sound reasoning principles that overapproximate, recently, incorrectness logic (IL) for completeness has gained more attention. However, techniques for reasoning about the incorrectness in object-oriented (OO) languages remain unexplored. The main challenge is integrating IL with OO concepts like inheritance and method overriding, which are crucial for supporting class hierarchies that facilitate the reuse of common data and methods. We present a mechanism [12] for specifying normal and abnormal executions of OO programs using ok and err. Our approach introduces subclass reflection with dynamic views and an adapted subtyping relation for under-approximation, addressing both OOP aspects (e.g., behavioral subtyping and casting) and under-approximation (e.g., dropping paths). Subsequently, we present an IL specification inference system [10] that automatically generates specifications and supports a push-button bug detection tool. By encoding type information into bi-abductive reasoning and propagating type constraints, our system efficiently identifies bugs from improper casting usage, which existing techniques cannot address. Additionally, it reduces false positives while uncovering more true bugs by retaining OO-type information. Experimental results indicate that our approach detects 400% more class-cast exceptions compared to *Error Prone* (by Google) and improves null-pointer exception precision by 24.4% over *Pulse* (by Meta).

Program Repair guided by CTL Properties. My interests also encompass *Computational Tree Logic* (CTL), which is founded on a branching concept of time, i.e., at each moment, there may be several different possible futures. Many CTL properties, such as reachability, termination, invariants, and responsiveness, are commonly specified in infinite-state programs. We suggest a mechanism for the automated repair of real-world programs guided by CTL properties. Our repair framework [11] is based on Datalog, a widely used logical inference language for program analysis, which readily supports nested CTL via stratified negation. Specifically, we encode the



program and CTL properties into Datalog facts and rules and perform the repair by modifying the facts to pass the analysis rules. The repair is discharged by an extended *Symbolic Execution of Datalog* (SEDL). This work focuses on proving both safety and liveness properties where loops are handled via a novel summarization, represented by a *guarded ω-regular language*. Unlike existing loop summaries, which do not explicitly capture non-terminating behaviours, we capture both terminating and non-terminating behaviours in a (guarded) disjunctive form. Given the undecidable nature of termination analysis, it outputs "Unknown" when there exists a path for which we cannot conclusively prove either termination or non-termination. This work advances existing repair techniques to encompass analyses defined by both least-fixpoint and greatest-fixpoint semantics.

Plans for Future Research

I envision several key directions for future work that will enhance the capabilities of program analysis and automated reasoning. These directions align with the overarching goal of improving software correctness and reliability in complex systems, as well as advancing logic-augmented generation for large language models (LLMs).

Large Scale Temporal Verification via Precise Loop Summaries. Termination is a sub-problem of temporal properties because it directly influences the ability to ensure that a program eventually reaches a desired state or outcome. I propose several concrete directions for achieving scalable temporal verification via loop summaries.

(1) **Large Scale (Non-) Termination Analysis.** Many real-world programs still suffer from vast consequences caused by non-termination bugs. While various termination-checking tools have proven effective on well-established benchmarks, recent studies [14] indicate that these tools must be more effective with real-world projects and benchmarks. Therefore, existing termination analysis tools must be enhanced to improve their scalability and applicability to real-world projects. Furthermore, errors in general programming features, such as bit-level arithmetic, heap usage and recursive functions, etc., should be paid more attention to in future termination analysis research. A combination of my existing research on compositional verification and effective loop summarization — for both terminating and non-terminating behaviours — can help overcome the limitations of existing tools and contribute to a more robust termination analysis.

(2) **More Precise Safety Checking.** My previous work introduced ProveNFix, the first compositional temporal analysis tool designed for large scale programs [6]. It detects general safety property violations, including null pointer dereferences, resource leaks, and memory leaks. However, similar to many analysis tools that rely on incorrectness logic [15] [12], ProveNFix handles loops via unrolling. Such a design choice results in many false negatives, i.e., undetected bugs, in both theory and practice, as it under-approximates loop behaviour by considering only a finite number of execution instances. I believe these false negatives can be significantly reduced by employing more accurate loop summaries derived from the methods in (1).

(3) **Large Scale Liveness Checking.** Verifying liveness properties in protocol implementations is essential for ensuring progress, avoiding starvation, verifying interactions, etc. Existing works for capturing liveness bugs are based on grey-box fuzzing [16]. While testing-based approaches like fuzzing are effective, they often struggle to prove the absence of bugs. Therefore, I plan to pursue the first modular liveness-checking tool for protocol implementations. The key insight is that most liveness properties can be reduced to a set of safety properties with the help of ranking functions [17]. More specifically, given any global liveness property and a large codebase that contains many function definitions, a specification inference process projects the global (liveness) requirement to individual functions, and such a projection creates modular (safety) specifications for each function. These generated specifications can be further used for bug detection/repair.

Advanced Logic for Specification and Practical Inference Mechanisms. Staged specification [7, 8, 9] involves decomposing a program's specification into multiple stages, each focusing on different aspects or levels of abstraction. This approach allows for more granular and modular reasoning about different components or phases

of the program's execution. The capabilities of staged specifications have the potential to benefit more language features such as asynchronous/concurrent programs, other implementations for effects handlers, etc.

(1) **Staged Specification for Concurrency.** Asynchronous programs involve cooperative concurrent operations, such as pausing/resuming, event-driven programming, parallel tasks, and switching between multiple execution paths. Managing the interplay between these operations presents significant challenges in specification and verification due to their inherent complexity and non-deterministic nature. The staged specification approach offers a viable solution by dividing the specification into distinct stages, each targeting specific segments of the program's behaviour. This method is advantageous for verifying preemptive asynchronous programs with complex execution semantics. Breaking down the specification into manageable stages provides a structured framework for navigating intricate interactions and ensuring correctness.

(2) **Staged Specification for Low-level Code.** WebAssembly (Wasm) is a low-level, portable code format that delivers near-native performance and serves as a compilation target for various source languages. Previously, Wasm lacked direct support for non-local control flow features like async/await, generators, and lightweight threads. However, recent advancements introduced WasmFX [18], which provides a universal target for these features through effect handlers, enabling compilers to translate them directly into Wasm. Notably, the use of staged specifications could aid in verifying low-level abstractions in WebAssembly, necessitating a deeper understanding of its execution model, including stack operations and memory management.

(3) **Lemma Synthesis for Staged Specification.** As previously noted, staged specifications benefit from automated inference, requiring only minimal specifications such as auxiliary lemmas. However, crafting these lemmas can be challenging due to their complexity and the nuanced understanding needed to ensure correctness. To address this issue, employing a search-based or data-driven approach that utilizes input-output examples could significantly enhance the automation of the verification process. These methods streamline lemma generation by leveraging existing data and patterns, thereby reducing the need for manual effort.

Expressiveness & Modularity of Future Conditions. The existing application for future conditions has demonstrated its effectiveness in specification inference and bug detection, guided by temporal logic properties such as "eventually, the allocated memory will be freed" and "always, there is no null pointer dereference" [6]. Although it holds potential for various contexts in program analysis, several fundamental directions could enhance the usability of future conditions. Firstly, its dependence on pure arithmetic and temporal constraints represented as regular expressions restricts its capability to analyze dynamic resource management scenarios, including aliasing and reassignment operations. To address this issue, I plan to enhance the expressiveness of future conditions by incorporating separation logic. This approach will enable better tracking of mutations to local and global variables as well as the aliasing relationships among these variables. Secondly, the existing reasoning system of future conditions has not achieved full modularity. Whenever there is a function call, the remainder of the code must be analyzed to verify the future condition. As a result, certain parts of the code are subjected to multiple analyses, leading to inefficiencies and potential redundancy. To address this issue, I plan to extend the existing Hoare-style reasoning rules by associating future conditions with the postconditions. This enhancement will facilitate a compositional reasoning system that aims to achieve full modularity, ensuring that each line of code is analyzed only once and can be replaced by its verified specification.

Detecting and Reducing Hallucinations in LLMs Through Logical Reasoning. It is known that LLMs struggle with generating hallucinations, i.e., coherent yet factually inaccurate outputs. A major concern is fact-conflicting hallucination (FCH), where LLMs produce content contradicting ground truth facts. The existing work [19] addresses this issue by creating a testing framework that builds a factual knowledge base from sources like Wikipedia. It uses logical reasoning rules to transform and augment this knowledge into a large set of test cases with ground truth answers. However, its capability to evaluate the complex logical reasoning of LLMs is limited,

as its rules only cover simple relations like negation and symmetry, etc. Meanwhile, LLMs still struggle with more complex logical reasoning, such as temporal reasoning, due to the lack of understanding of time and the semantics of temporal operators. To detect such temporal hallucinations, I propose to automatically generate test cases that effectively ensure a more robust evaluation of the LLMs' ability to handle reasoning tasks and identify factual inconsistencies. By applying reasoning rules derived from temporal logic, one can mutate and expand the initial seed data from the knowledge base, enhancing the diversity and complexity of the test scenarios.

To further mitigate temporal hallucinations, I plan to integrate formal logic into large language models (LLMs) through "Logic-Augmented Generation," which aims to improve their temporal reasoning capabilities. Specifically, if LLMs can effectively decompose the components of a temporal query — such as temporal operators and atomic propositions — we could instrument the temporal reasoning process with formal methods like Prolog. This approach would enhance the correctness and reliability of responses, with any uncertainty arising only from the decomposition phase, while ensuring that the temporal reasoning remains sound and complete.

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