David Van Horn Research Statement

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Since the late 1960s, computer scientists have struggled with what has come to be known as the *software crisis* [32]: an ever increasing reliance of society on computing systems, coupled with the growing gap between the ubiquity and power of these systems and the difficulty of writing useful and efficient programs economically. In his 1972 ACM Turing Award lecture [11], Edsger Dijkstra remarked: "To put it quite bluntly: as long as there were no machines, programming was no problem at all; when we had a few weak computers, programming became a mild problem, and now we have gigantic computers, programming has become an equally gigantic problem." In the intervening decades, computing systems have radically proliferated, our reliance upon them dramatically deepened, and the "gigantic" computers of Dijkstra's time are infinitesimal compared to today's. In short, the software crisis has flourished and overcoming it is all the more critical.

I believe the solution to this crisis rests in the effective use of programming language (PL) technology, which has the potential to turn the power of computing toward resolving the very crisis it creates. PL history has marched steadily from low-level machine-oriented languages to high-level languages enabling more abstract forms of thinking; computation bridges the gap between them. Today, programming languages and their associated tools can guide good design, categorically eliminate large classes of errors and vulnerabilities, and provide substantial aid to programmers throughout the software development life-cycle.

I work on the design, implementation, and use of programming languages and program analysis with the goal of making the construction of reusable, trusted software components possible and effective. I focus on modern, high-level languages and automated techniques for analyzing, verifying, and debugging programs. The following outlines the major themes of my work in chronological order, culminating in my vision to build gradual verification-integrated programming languages enabling pathways to verified programming at every point along the spectrum from scripting languages to theorem proving languages.

Computational complexity of program analysis. Program analysis is the art and science of making (software that makes) useful predictions about what a program will do when run. One of the most common forms is *flow analysis* (sometimes called *control-* or *data-flow* analysis, a distinction without a difference in functional and object-oriented languages, which are *higher-order*: they include computational values). Flow analysis predicts what possible values a given expression may take on when run. It is a fundamental form of analysis that essentially underpins any other kind of prediction. Higher-order flow analysis has been widely studied since 1981 [24] with many variants occupying points along a spectrum of precision and performance.

One of the most famous classes of flow analyses is Shivers' kCFA hierarchy, a family of analyses that—for some constant k—distinguishes k-levels of function call contexts before resorting to a coarse-grained approximation. As a PhD student, I was struck by a passage in Shivers' 25-year retrospective on kCFA [39]:"It did not take long to discover that the basic analysis, for any $k > 0$, was intractably slow for large programs. In the ensuing years, researchers have expended a great deal of effort deriving clever ways to tame the cost of the analysis." Despite the extensive literature, very little was known about the computational complexity of performing flow analysis, which would shed light on whether "taming the cost" was even possible.

In my dissertation, I established tight bounds on the complexity of kCFA and related analyses [47]. I proved for any $k > 0$, computing kCFA was complete for EXPTIME [49], demonstrating empirically observed increases in costs can be understood analytically as inherent in the approximation problem being solved. For 0CFA, I proved it PTIME-complete [48], and showed the result was robust for every known variant of 0CFA that made further approximations [50]. I derived a type-based variant of 0CFA for programs adhering to a very restricted syntactic discipline that was in LOGSPACE, which provides some evidence that there's no good 0CFA-like analysis with

complexity below PTIME for general programs. While these results appear negative, they yielded insights into better designs. After the EXPTIME-completeness result, we designed an alternative kCFA hierarchy with polynomial-time upper-bounds for any k and empirically showed it computes more efficiently without losing precision compared to Shivers' kCFA [30].

Methodologies for building analyzers. One of the main impediments to building sound software analysis tools is that designing these predictive models traditionally requires highly specialized training, such as a doctorate, not just in PL, but in program analysis specifically. Expressive languages complicate the problem further, limiting its impact on modern high-level languages.

Based on insights gained during my complexity theory investigation, we designed a methodology for developing sound program analyzers using *abstract machines*, a semantic model widely used in the PL research community. The approach, dubbed *abstracting abstract machines* [51], starts from familiar territory—the stuff of undergraduate PL courses—and uses a series of simple program transformations applied to the machine semantics of a language. Each transformation is easily justified as semantics preserving, until a final "finitization" step that incorporates approximation, rendering the models computable. One of the main strengths of AAM is it reduces analysis design, even for sophisticated language features, down to formulating a machine semantics for those features: something the PL community excels at with a large literature on tools and techniques. The original paper includes a series of vignettes applying the technique to analyze stack inspection, garbage collection, laziness, and control operators, each of which would previously be considered a contribution on its own. The AAM technique has thus expanded both the community capable of designing analyzers and the set of language features subject to program analysis.

My research on AAM has been well-received and influential. The original ICFP paper was selected to appear in *Communications of the ACM: Research Highlights* [52], which selects a paper monthly "from all areas of computer science to be highlighted as especially important and relevant for the 80,000+ members of the ACM." It was invited to the special issue of *JFP* devoted to ICFP'10 [53]. It forms the basis of several PhD theses that build upon or employ the approach [1, 5, 12, 16, 18, 25, 26, 38, 42], as well as many papers. It has been the subject of conference tutorials, invited lectures, and research summer schools. The technique has been applied by others to a number of languages such as Scala, Erlang, Java, and JavaScript. It has influenced the design of tools developed at HP Fortify, Github, and Google. I consistently receive feedback praising the work as being one of the most accessible and lucid accounts of how to build an abstract interpreter.

Since conceiving AAM, we have applied and extended it in a number of settings, such as reasoning about concurrency [31], exceptions [29], and detecting malware in Android applications [28, 27]. Thanks to the close correspondence between AAM and the underlying semantics, it is possible to import well-known optimization techniques to speed up analysis [20]. Moreover, the simplicity has enabled strong advances, both in the theory and practice of higher-order program analysis. In particular, we achieved so-called "pushdown" analysis, which essentially replaces a finite-state approximation with that of a pushdown automata [13, 14, 19, 21]. This results in perfectly precise analysis of function calls and returns. Recently, we have shown this added power can be achieved with the same theoretical and observed cost as the finite-state approach, giving a cubic-time algorithm [17]. Finally, we have demonstrated the AAM steps can be applied starting from a high-level compositional interpreter rather than a low-level machine. Remarkably, this tack results in an analyzer that inherits the pushdown property from the defining language rather than through any explicit mechanism [8]. (Two of these paper were invited to special issues of *JFP* [21, 9].)

Verifying behavioral properties of programs. Modern software is developed from reusable components, which communicate in diverse ways. This necessitates well-defined interfaces and mechanisms to discern faulty components when an error occurs. Software contracts [15] express these invariants and agreements between components and ensure they have sensible semantics even in a higher-order setting. Among the subtle issues addressed by contracts is blame assignment, which determines which component is at fault when a contract is violated. Contracts thus form a rich specification language enables a marketplace of reusable software components with a proper account of culpability.

Over the past several years, we have developed techniques for automatically verifying software contracts. The goal has been to leverage contracts to enable a marketplace of *verified* reusable components that are formally proven to satisfy their contracts. Two paramount technical obstacles needed to be overcome to achieve this goal. First, the expressivity of contracts, while crucial for the construction of reliable components, thwarts static reasoning about programs and incurs significant run-time monitoring costs. Second, the expressivity of higher-order languages, a mainstay of modern industrial software, thwarts static reasoning about contracts, despite the availability of mature automated tools and techniques.

To overcome these obstacles, we developed a novel symbolic semantics for modularly executing programs with contracts at its interface boundaries [44, 43]; one of the key contributions was a treatment of higher-order symbolic functions. When combined with existing abstraction techniques, such as AAM, the symbolic semantics becomes an effective automated verification engine for proving the absence of run-time errors, including contract failures [37]. (This paper was accepted to a special issue of *JFP* [35].) Despite the source language's use of higher-order values, the verification technique is able to side-step the need for a higher-order solver, thereby leveraging powerful off-the-shelf SMT solvers. The approach is also useful for generating concrete, potentially higher-order, counterexamples—inputs that witness a run-time failure—for programs, and we proved a strong relative completeness result demonstrating counterexample generation depends only upon the power of a first-order solver for the base types of a language [36]. Recently, the approach has been extended to handle stateful programs effectively [34]. This work is formalized and proved sound with mechanically checked proofs; prototypes were accepted by artifact evaluation committees at PLDI and POPL. The empirical evaluation shows the approach effective in eliminating 99.94% of run-time checks in a suite of realistic programs.

Verified and extensible analyzers. Critical software systems require high-assurance tools to verify the absence of undesirable behavior such as crashes, security vulnerabilities, or privacy lapses. While many of these tools exist, few are verified, calling in to question the trustworthiness of their results, and consequently, the reliability of the critical systems. This situation persists despite several decades of research and investment in independent areas of mechanic verification and sound program analysis. The main problem is each aspect is on its own considered a difficult undertaking, technically and economically.

We have made progress toward a solution in two important regards: we integrated techniques from mechanical verification and program analysis allowing existing correct-by-construction methods for designing analyzers to be carried out in a dependently-typed proof assistant with ability to extract certified implementations; we have developed a theory and mechanism for extensible program analysis construction that enables analyzers to be constructed correctly and automatically out of a combination of existing analysis components.

Abstract interpretation (AI) is a theory of sound approximation widely used in semantics, formal verification, and static analysis. Since its debut in the late 1970s [3, 4], efforts to combine AI and mechanized verification have achieved limited success, either sacrificing generality of the theory or the ability to extract certified analyzers from existing proofs. Our theory of *constructive Galois connections* achieves both [6]. (This paper was accepted to a special issue of *JFP* [7].) The key insight was to use monadic discipline to isolate and navigate between specifications and implementations. We were able to carry out two case studies of deriving certified analyzers in a dependently typed programming language. Monadic transformers were employed in our work on *Galois transformers* to achieve modular and extensible program analyzers that makes it possible to design analysis components that are reusable in their implementation and metatheory [10]. We are currently exploring the use of program synthesis to make building analyzers even easier.

Gradual verification: from scripting to proving. Programmers are rapidly adopting expressive, dynamically typed, higher-order functional and object-oriented programming languages for their everyday development tasks. Over time, these programs are often fortified with static type checking by migrating programs using *gradual types*, a technique first developed in the research community, but now widely used by the largest industrial software development companies. Unfortunately, there are limits both to what properties gradual types can validate and the help they can provide programs as they engage in the migration process. In parallel, researchers have developed sophisticated next generation programming languages with integrated verification features. These languages are able to validate much

stronger claims about the correctness of software, but their industrial adoption has lagged far behind gradual typing. Consequently, verification is not being integrated in the everyday lives of programmers and the quality and reliability of software suffers because of it. This represents a tremendous missed opportunity considering the rapid advancement of automated verification techniques.

My future work aims to provide foundational theories, pragmatic tools, and a pedagogical framework for closing the expressivity gap between the everyday languages of programmers and these verification-integrated languages, enabling pathways to verified programming at every point along the spectrum scripting languages to theorem proving languages. Doing so will require the synthesis of many of my prior themes on behavioral verification, abstract interpretation, and mechanization. It will also require new language abstractions for enforcing run-time properties corresponding to the static properties guaranteed by verification-integrated languages. As a first step in this direction, I have recently developed a run-time mechanism for enforcing termination [33], which enables the gradual integration of partial and total program components.

Other work. In addition to the above, I have worked on incremental computation [23], online-verification validation [22], probabilistic languages [46], mechanical theorem proving [54], programming pedagogy [45], gradual refinement types [55], semantics of laziness [2], and temporal model checking [40, 41].

Publications and funding. Carrying out this work has resulted in 29 peer-reviewed conference or journal publications. This includes one paper in the *Communications of the ACM: Research Highlights* and multiple papers in all four of the flagship SIGPLAN conferences: ICFP (8), OOPSLA (4), POPL (2), and PLDI (2), including a Distinguished Paper at OOPSLA. My ICFP papers have been selected for special issues of the *Journal of Functional Programming* five times. Work on "abstracting abstract machines" has featured prominently in nine PhD theses to date and has been the subject of several invited lectures, research summer schools, and conference tutorials.

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