Research Statement

My research is in the area of programming languages, compilers, and security. More specifically, I work in static program analysis, which reasons about program behavior *before program execution*. We apply program analysis techniques to improve software security and productivity, and data privacy.

1 Present and Past Research

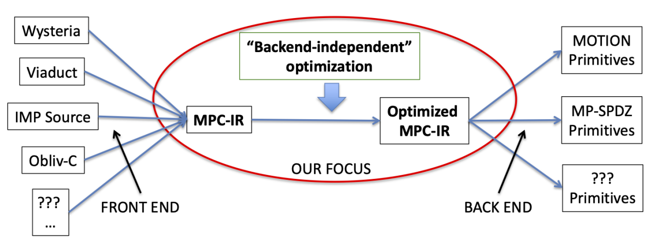
I summarize, in reverse chronological order, the three major research thrusts I have worked on since my promotion to associate professor. I have led the projects working with diverse teams of graduate and undergraduate students while fostering collaboration with leading researchers in each area.

1.1 Compilation and Optimization for Multi-Party Computation

Motivation Multi-party computation (MPC) allows N parties $p_1, \ldots, p_N$ to perform a computation on their private inputs securely. Informally, security means that the secure computation protocol computes the correct output (correctness) and it does not leak any information about the individual party inputs, other than what can be deduced from the output (privacy).

MPC theory dates back to the early 1980's. Long in the realm of theoretical cryptography, MPC has seen significant advances in programming technology in recent years — it has been employed in real-world *secure computation* scenarios such as auctions, biometric identification, and privacy-preserving machine learning. Unfortunately, MPC programming is still complex and requires extensive knowledge of programming systems and cryptography. The goal of our research is to bring MPC programming technology to a level where programmers can write *secure* and *efficient* programs without commanding extensive knowledge of cryptographic primitives.

Our Work *The problem, therefore, is to build high-level programming languages and optimizing compilers for MPC.* Our work focuses specifically on an intermediate language and what we call *backend-independent optimizations*, in a close analogy to *machine-independent* optimizations in the classical compiler. The following figure summarizes the key idea:



We emphasize the MPC-IR intermediate representation (IR) and optimization over MPC-IR. As in classical compilers, an IR is important because it enables reusability of language front ends and cryptographic back ends, as well as optimizations available at the IR level. We envision different front ends, including advanced front ends such as Wysteria and Viaduct, compiling into MPC-IR, and MPC-IR compiling into the leading cryptographic backends for MPC, MOTION and MP-SPDZ. MPC-IR exposes the linear structure of MPC programs, which simplifies program analysis and optimizations such as protocol mixing, SIMD-vectorization (which enables amortization of cost of cryptographic operations) and scheduling. In the same time, MPC-IR is sufficiently "high-level" and amenable to analyses and optimizations that take into account control and data flow in a specific program.

Protocol mixing is an MPC-specific optimization. In a nutshell, MPC programming supports different protocols of sharing and computation, and protocols have inherent differences. There are two basic approaches in MPC protocol design: (1) Yao's *garbled circuits* and (2) the secret-sharing paradigm known as GMW; GMW gives rise to two techniques, known as Boolean and Arithmetic. Very informally, the Arithmetic protocol allows for efficient arithmetic operations (e.g., multiplication) but inefficient boolean and logical operations (e.g., comparison and multiplexing). Alternatively, Yao's garbled-circuit protocol allows for less efficient arithmetic operations but more efficient boolean ones. One can convert data from the sharing scheme required by the Arithmetic protocol to the scheme required by the Yao protocol, but typically at a non-trivial cost.

The problem of assigning protocols to MPC-IR statements, along with necessary (minimal) share conversions, can be viewed as a program analysis problem. One notable result of our project is an algorithm that computes an optimal protocol assignment in polynomial time for 2 protocols [5]. Our other notable result is a compiler from a Python-like source (which we call IMP Source, after the well-known simple imperative language IMP) into the two leading MPC backends, MOTION and MP-SPDZ; we formalize MPC-IR and build a SIMD-vectorization optimization that leads to significant performance improvement compared to iterative code [6]. Yet the problem of optimal protocol assignment for 3 or more protocols (in polynomial time) is still open, and we will continue to work on it. We are especially interested in integrating mixing (even heuristic mixing) with SIMD-vectorization and other optimizations.

Publications The work on optimal mixing appeared in CCS'19 (ref. [5]) and the work on compilation and SIMD-vectorization will appear in CCS'23 in November (ref. [6]).

1.2 Principled and Practical Static Analysis of Python

Motivation While Python is a widely used programming language, particularly in data science programming, principled static analysis for Python is lacking. Python, by virtue of being a dynamic language, does not require type annotations by the programmer, yielding undocumented code and delaying error reporting until runtime. Static analysis can bring significant benefits to Python developers: it can help infer types for variables and functions and significantly improve readability of code; it can help extract specifications of complex libraries and catch bugs and misuse before program execution.

For example, a common scenario arising with the popular SKLEARN machine learning library is a pipeline where the programmer has misconfigured one of the components, i.e., she has specified hyperparameter values that violate certain constraints of the component. Early components take a long time to train, only to reach the misconfigured component, which terminates the pipeline losing all prior training work. We set out to extract hyperparameter constraints from machine learning libraries and encode checks that detect misconfiguration *before* program execution.

We expected to reuse existing results, only to discover that even classical analyses such as 3-address code translation and points-to analysis for Python remained open problems. Many existing analyses are ad-hoc traversals of the Abstract Syntax Tree (AST); they do not elaborate on the exact statements and expressions they analyze or the traversal semantics. Analysis is largely ad-hoc and unsound.

Our work *Therefore we ask, can we define static analysis for Python in a (more) principled way? Is it possible to reason about what parts of a Python program are analyzed soundly and what parts are analyzed unsoundly?* Principled reasoning grounds the analysis and builds confidence in analysis results, particularly when (speaking very informally) results originate from sound parts of the program and remain "untainted" by flows from unsound parts.[1] It enables analysis reusability and extensibility with semantics and interpretation of new language features.

Our work takes a step in this direction. We define PetPy, a minimal Python syntax where we break Python constructs into *interpreted* and *uninterpreted* ones. *Interpreted* constructs receive a sound and precise interpretation; these are attribute accesses, calls, assignments and other constructs that are ubiquitous in code and affect flow of references. In contrast, uninterpreted ones are treated to a common fall-through interpretation, which, in general, is neither sound nor precise; examples of uninterpreted constructs (in our current treatment) are `while` statements and list comprehensions. We then define (1) 3-address code translation and (2) weakest precondition inference as principled interpretations over PetPy. While our analysis remains unsound, we elaborate on the exact constructs and interpretation semantics [12, 11]. Ultimately, we use the analysis to infer hyperparameter constraints encoded as exceptions in machine learning libraries, and check for misconfiguration before execution.

We also define what we call *soundness analysis* to reason about the inferred weakest preconditions. The weakest precondition analysis is a standard backwards reasoning: it starts at an exception and propagates a formula Q backwards towards the beginning of the function. For each statement s it steps over, where s can be a call, a `for`-loop, an assignment, etc., the analysis reasons whether the locations modified by s intersect with the locations read by Q. If the answer is yes, then Q becomes unsound.

Publications The work was published at ISSTA'22 (ref. [12]) and won an ACM SIGSOFT Distinguished Paper Award. Our extended version was just accepted to Wiley Software: Practice and Experience (SPE) (ref. [11]). In addition, our analysis uncovered bugs in both code and documentation in popular machine learning libraries. We submitted issues and pull requests to SKLEARN, TENSORFLOW, NUMPY, and IBM's LALE framework, which the developers promptly merged.

1.3 Inference and Checking of Context-Sensitive Pluggable Types

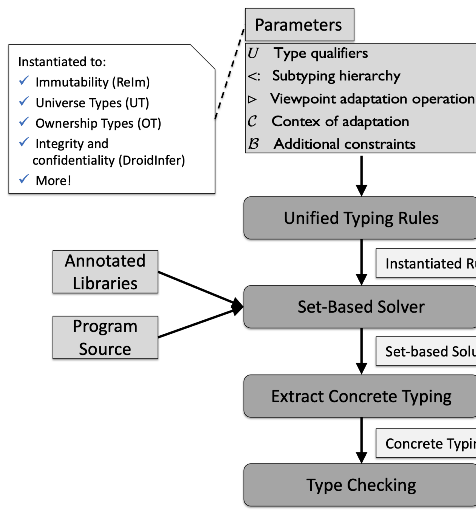
Motivation Static type systems improve software productivity and security by catching errors and security vulnerabilities *before* program execution. They typically require writing *type annotations* and the process can be burdensome to the programmer. Consequently, dynamically-typed languages like Python forgo static type systems and relegate essentially all type checking and error prevention to the runtime. Statically-typed languages like Java aim to lower the annotation burden as well — they check for many errors, but not all; for example, they do not check for unintended mutation or flow of sensitive values to untrusted components.

Pluggable types enhance a static type system. They can be *plugged* seamlessly into an existing program to catch bugs beyond the capabilities of the underlying static type system (if there is one). Notably, the CHECKER FRAMEWORK provides pluggable type systems that target different classes of Java bugs, including unintended mutation and SQL injection vulnerabilities. A downside is that a pluggable type system, by virtue of being a static type system, typically requires annotations by the programmer.

Our work Our work focuses on *type inference. Can we design pluggable type systems that require a minimal number of annotations, even no annotations at all?* I led a project on a pluggable types framework that focused on *context-sensitive* reasoning (context-sensitive reasoning allows for verifying a larger number of programs as safe, as opposed to context-insensitive reasoning, which may flag safe programs as buggy). A type system designer specifies the essential components of a type system in the framework: the types, subtyping hierarchy and the context adaptation operation that enables

[1] We remark that "sound" in our treatment is in fact "soundy" in the spirit of the Soundiness manifesto [7]. Soundiness refers to static analyses that intentionally under-approximate certain language features because handling of those features over-approximately would render the analysis useless.

context-sensitive reasoning. A programmer may add a small number of annotations in their program, or in many cases of type systems we designed, they add no annotations at all. The framework then automatically infers the rest of the annotations and type checks the program — it either verifies the program as safe (of the class of bugs that the type system checks for, e.g., unintended mutation), or flags errors. The figure illustrates our framework:



The framework is general and gives rise to concrete instantiations (a subset is shown above). One is ReIm, a novel type system for reference immutability, and ReImInfer, the corresponding inference tool [4]. One can specify a small set of references as *immutable* and ReImInfer either flags violations of their immutability, or verifies that they remain immutable across all program runs. The programmer can specify no annotations at all in which case ReImInfer infers a typing with a maximal number of immutable references. An extension of ReImInfer infers *method purity*, a fundamental analysis applicable in a variety of software engineering and compiler tasks. Other instantiations of the framework are the inference algorithms for classical Ownership types and Universe types, including the first polynomial-time algorithm for the inference of Universe types [1]. Another instantiation is DroidInfer, an information flow type system and a corresponding inference tool that finds information leaks in Android apps [2]. DroidInfer assumes annotated Android libraries that specify *sources* of sensitive data (e.g., device identifier, phone number) and untrusted *sinks* (e.g., an untrusted url). It requires *no annotations* by the programmer. DroidInfer flagged dozens of leaks in apps from the Google Play store (e.g., an advertising server stealing the device phone number).

In later work we generalized a class of context-sensitive pluggable type systems (including ReIm and DroidInfer) into a positive-negative type qualifier system and we reduced the inference problem to a Context-Free-Language-reachability (CFL-reachability) problem [8, 9]. The reduction enables reasoning about the semantics of the qualifier system and drives a correctness argument.

Publications This work appeared in OOPSLA'12 and '20 (refs. [4] and [9]), ECOOP'12 and '18 (refs. [1] and [8]), and ISSTA'15 (ref. [2]). An overview of our framework and a demo of the ReImInfer tool were published in the New Ideas and Tool Demo tracks of FSE'12, respectively (refs. [10] and [3]). This work has generated about 350 citations.

2 Future Research Directions

While I will continue to work in compilers, programming languages and program analysis, my core areas of expertise and interest, I have also ventured into the new era of machine learning and quantum computing. An important application of our program analysis for Python is improving robustness of machine learning libraries. We have contributed pull requests to widely-used libraries such as Sklearn and we will continue to build program-analysis-based tools. I have started a collaborative project with Prof. Stacy Patterson on privacy-preserving vertical federated learning using differential privacy and multi-party computation. In addition, I am looking forward to collaborating with IBM and RPI researchers on quantum computing. I am, above all, looking forward to applying my expertise in programming languages and compilers towards building programming systems for the IBM System One quantum computer coming to campus.

Below I describe in detail the concrete extensions of our work on compilers for secure computation and principled static analysis for Python.

2.1 Compilation and Optimization for MPC

One direction builds new intra-procedural analyses and optimizations over MPC-IR. In addition to SIMD-vectorization, we develop divide-and-conquer, scheduling, protocol mixing and other optimizations. We extend classical program analysis techniques to the unique setting and constraints of MPC, but we also develop new MPC-specific cost models and optimizations, and aim to explore combinations and ordering of optimizations, much in the vein of the classical compiler. The key premise is that the linear structure of MPC-IR is highly amenable to program analysis, accurate cost modeling and program synthesis and therefore these techniques can give rise to aggressive and provably optimal transformations.

Another direction builds a theoretical foundation for proving that the transformations over MPC-IR (e.g., vectorization, protocol mixing) preserve program semantics. The formalization of MPC-IR we have developed is a step forward; we aim to build an Abstract Interpretation-based framework for reasoning about optimizing transformations.

The third direction extends intra-procedural reasoning to the inter-procedural case. We enhance the source language with a notion of a *secure* component that executes under expensive secure computation protocols and a *plaintext* component, and enforce interaction and value flow between the two components with a flexible polymorphic (i.e., context-sensitive) type qualifier system. The type system is expressed within the pluggable types framework described in Sec. 1.3. A key goal is to integrate the type qualifier system (operating at a higher level) with backend-independent optimizations (at the lower level), towards an expressive and efficient programming system.

2.2 Principled Static Analysis of Python

I will also continue my work on principled and practical static analysis of Python. One direction develops classical analyses such as points-to analysis on top of PetPy and applies the analyses towards software tasks — type inference, specification inference and array shape analysis which have applications in reasoning about correctness of machine learning libraries.

Another direction expands on our "soundness" analysis. We aim to build a framework that estimates soundness of a static analysis for Python. Given an analysis, it will classify analysis results as sound and unsound based on *assumptions the analysis makes in its interpretation of Python constructs.* The analysis can make stronger assumptions and classify a larger subset of results as sound, and vice versa, it can make weaker assumptions resulting in a smaller subset of results deemed sound. In the most severe case the analysis will make no assumptions about the fall-through common interpretation; thus, results that interact with uninterpreted statements and expressions will be marked unsound. It is also important to allow for realistic assumptions. In more realistic cases the analysis will make certain assumptions — e.g., our soundness analysis for weakest preconditions does assume that the common fall-through implementation captures flow of references and reference mutation correctly.

This is a difficult problem. We aim to expand on principled analysis — in addition to specifying interpretation (which is mostly standard) we aim to build a framework for specifying assumptions. At the same time, the analysis will remain practical and will tackle real-world, widely-used Python software systems. The goal is to ground practical analysis around the PetPy syntax and allow for clear and concise statement of interpretation semantics and assumptions; this will facilitate adoption, extensibility with new language features and application towards real-world software tasks.

References

[1] Wei Huang, Werner Dietl, Ana L. Milanova, and Michael D. Ernst. Inference and Checking of Object Ownership. In James Noble, editor, *ECOOP 2012 - Object-Oriented Programming - 26th European Conference, Beijing, China, June 11-16, 2012. Proceedings*, volume 7313 of *Lecture Notes in Computer Science*, pages 181–206. Springer, 2012.

[2] Wei Huang, Yao Dong, Ana L. Milanova, and Julian Dolby. Scalable and Precise Taint Analysis for Android. In Michal Young and Tao Xie, editors, *Proceedings of the 2015 International Symposium on Software Testing and Analysis, ISSTA 2015, Baltimore, MD, USA, July 12-17, 2015*, pages 106–117. ACM, 2015.

[3] Wei Huang and Ana L. Milanova. ReImInfer: Method Purity Inference for Java. In Will Tracz, Martin P. Robillard, and Tevfik Bultan, editors, *20th ACM SIGSOFT Symposium on the Foundations of Software Engineering (FSE-20), SIGSOFT/FSE'12, Tool Demo Track, Cary, NC, USA - November 11 - 16, 2012*, page 38. ACM, 2012.

[4] Wei Huang, Ana L. Milanova, Werner Dietl, and Michael D. Ernst. Reim & ReImInfer: Checking and Inference of Reference Immutability and Method Purity. In Gary T. Leavens and Matthew B. Dwyer, editors, *Proceedings of the 27th Annual ACM SIGPLAN Conference on Object-Oriented Programming, Systems, Languages, and Applications, OOPSLA 2012, part of SPLASH 2012, Tucson, AZ, USA, October 21-25, 2012*, pages 879–896. ACM, 2012.

[5] Muhammad Ishaq, Ana L. Milanova, and Vassilis Zikas. Efficient MPC via Program Analysis: A Framework for Efficient Optimal Mixing. In Lorenzo Cavallaro, Johannes Kinder, XiaoFeng Wang, and Jonathan Katz, editors, *Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security, CCS 2019, London, UK, November 11-15, 2019*, pages 1539–1556. ACM, 2019.

[6] Benjamin Levy, Muhammad Ishaq, Benjamin Sherman, Lindsey Kennard, Ana L. Milanova, and Vassilis Zikas. COMBINE: COMpilation and Backend-INdependent VEctorization for Multi-Party Computation. In *To appear in the 2023 ACM SIGSAC Conference on Computer and Communications Security, CCS 2023, Copenhagen, Denmark, November 26-30, 2023*. ACM, 2023.

[7] Benjamin Livshits, Manu Sridharan, Yannis Smaragdakis, Ondřej Lhoták, J. Nelson Amaral, Bor-Yuh Evan Chang, Samuel Z. Guyer, Uday P. Khedker, Anders Möller, and Dimitrios Vardoulakis. In Defense of Soundiness: A Manifesto. *Commun. ACM*, 58(2):44–46, jan 2015.

[8] Ana L. Milanova. Definite Reference Mutability. In Todd D. Millstein, editor, *32nd European Conference on Object-Oriented Programming, ECOOP 2018, July 16-21, 2018, Amsterdam, The Netherlands*, volume 109 of *LIPIcs*, pages 25:1–25:30. Schloss Dagstuhl - Leibniz-Zentrum für Informatik, 2018.

[9] Ana L. Milanova. FlowCFL: Generalized type-based reachability analysis: Graph reduction and equivalence of cfl-based and type-based reachability. *Proc. ACM Program. Lang.*, 4(OOPSLA):178:1–178:29, 2020.

[10] Ana L. Milanova and Wei Huang. Inference and Checking of Context-Sensitive Pluggable Types. In Will Tracz, Martin P. Robillard, and Tevfik Bultan, editors, *20th ACM SIGSOFT Symposium on the Foundations of Software Engineering (FSE-20), SIGSOFT/FSE'12, NIER Track, Cary, NC, USA - November 11 - 16, 2012*, page 26. ACM, 2012.

[11] Ingkarat Rak-amnouykit, Ana Milanova, Guillaume Baudart, Martin Hirzel, and Julian Dolby. Principled and Practical Static Analysis for Python: Weakest Precondition Inference of Hyperparameter Constraints. *Accepted for publication in Wiley Software: Practice and Experience (SPE)*, 2023.

[12] Ingkarat Rak-amnouykit, Ana L. Milanova, Guillaume Baudart, Martin Hirzel, and Julian Dolby. The Raise of Machine Learning Hyperparameter Constraints in Python Code. In Sukyoung Ryu and Yannis Smaragdakis, editors, *ISSTA '22: 31st ACM SIGSOFT International Symposium on Software Testing and Analysis, Virtual Event, South Korea, July 18 - 22, 2022*, pages 580–592. ACM, 2022.