

RESEARCH STATEMENT

Abdul Haddi Amjad

<https://people.cs.vt.edu/~hadiamjad/>

The vision of my research is to develop frameworks that enhance the privacy and security of online websites through advanced program analysis. My work integrates techniques from software debugging and testing into the domains of web security and privacy, bridging two traditionally distinct areas to make the web safer and more privacy-preserving. This interdisciplinary approach has resulted in my research appearing in top-tier venues across both software engineering (ICSE, FSE) and web security and privacy (IMC, PETS, CCS).

Overview. Modern websites often provide free services, yet nearly every online interaction now involves the collection and processing of personal user data. To facilitate this, websites rely extensively on JavaScript, whose size and complexity have expanded dramatically in recent years [4], extending far beyond its original purpose of enabling interactive functionality. This evolution has led to the widespread integration of third-party JavaScripts for analytics, advertising, and user tracking, embedding data collection code deeply into the operational fabric of the modern web. Such extensive tracking enables entities across websites to construct detailed user profiles and targeted content that can shape and even bias user behavior, raising fundamental concerns about privacy and individual autonomy in the modern web. These concerns are further amplified by the rise of browser-based intelligent agents, such as Atlas by OpenAI, which automate user interactions and expand the surface for data collection and inference.

Users today rely on tools such as ad-blockers and privacy-focused browsers, but these solutions are largely ineffective at addressing the root causes of data collection. Over a decade of research and industry effort has focused on superficial defenses that treat the symptoms of tracking rather than preventing it. Because these approaches are brittle, easily circumvented, and fail to address the underlying sources of tracking, users remain exposed to pervasive and opaque practices that are intrusive, difficult to detect, and increasingly hard to avoid. At the same time, protecting privacy often conflicts with the business models of free online websites that depend on collecting, analyzing, and sharing user data for revenue.

Contributions. The key insight of my research vision is to address privacy risks at their origin rather than through superficial solutions. This vision has grown increasingly relevant as privacy continues to gain national attention. The 2025 Mid-Year Review of U.S. State Comprehensive Data Privacy Law Updates, highlights expanding federal and state efforts to strengthen online privacy protections by expanding definitions of sensitive data, and enhanced safeguards for minors [22]. To realize this vision, my work applies program analysis techniques that combine dynamic analysis, semantic slicing, and lightweight JavaScript refactoring to treat websites as software systems where privacy-invasive behavior is localized and mitigated without breaking functionality. My research is organized around two central themes:

- The first theme focuses on using program analysis techniques to identify privacy-invasive code within modern web applications, where increasingly large and complex JavaScript code conceal data collection behaviors.
- The second theme examines how to refactor such code and validate the refactored scripts through testing to ensure that website functionality is preserved while privacy risks are effectively mitigated.

Theme I: Identifying privacy-invasive code through program analysis. Modern websites present significant challenges for identifying privacy-invasive behaviors due to their increasing JavaScript code obfuscation, minification, and dynamic nature. According to the Web Almanac, the median JavaScript payload on popular websites now exceeds several hundred kilobytes, with the widespread adoption of bundlers and build pipelines further blurring logical dependencies between scripts [4]. The growing adoption of minification removes meaningful variable names and structural cues, while obfuscation deliberately disguises control flow to hinder analysis [21, 3]. Additionally, the pervasive use of dynamic constructs such as `eval` [18], function constructors, and runtime script injection allows code to alter its own execution context, making static inspection alone inadequate for identifying privacy-invasive behaviors.

To address these challenges, my research applies program analysis techniques that combine static and dynamic analysis to uncover privacy-invasive behaviors within modern websites. Specifically, I perform cross-script call stack analysis, constructing timestamped, event-based execution graphs that capture interdependent script interactions. This approach collects complete call stacks, including the sequence of function calls leading to each event on a website, enabling precise differentiation between functions contributing to privacy-invasive behavior and those essential for legitimate functionality. By mapping these call relationships into structured execution graphs that incorporate DOM, network requests, JavaScript API calls, and inter-function dependencies, my analysis reveals fine-grained data flow patterns and exposes hidden privacy-invasive code paths that are otherwise difficult to detect.

Impact Summary

This research led to the discovery of previously unidentified privacy invasive JavaScript on websites, which we reported to the developers of ad-blockers, who acknowledged our findings [14, 12, 13, 15, 16]. Furthermore, our analysis uncovered a bug in one such ad-blocker (Ghostery [17]), demonstrating its inability to detect certain privacy invasive scripts that our approach successfully identified [8]. This line of work also resulted in my co-authorship of the *Privacy* [11] and *JavaScript* [10] chapters of the *Web Almanac 2024* edition, where I contributed empirical insights on web tracking and code transparency.

Theme II: Refactoring and testing privacy-invasive JavaScript. Once the privacy-invasive code has been identified, the next challenge is to refactor or replace it while maintaining the website’s legitimate functionality. Three factors make this task particularly challenging. First, the dynamic nature of JavaScript, characterized by runtime code generation, event-driven execution, and cross-script dependencies, complicates both refactoring and replacement. Second, applying such modifications at runtime without introducing performance delays or functional issues requires the development of lightweight and adaptive mechanisms. Third, conducting a comprehensive website breakage analysis requires careful evaluation to ensure that the refactored code continues to operate correctly across different user interactions and execution contexts.

To address these challenges, my research introduces a multi-stage approach. First, we design a graph based machine learning localization technique that captures the complete execution flow of a website when privacy-invasive code is triggered. This approach handles JavaScript dynamism by collecting detailed metadata at runtime, allowing accurate localization of privacy-invasive code. The localized code is then refactored by diffusing one of the function calls in the privacy-invasive call sequence to break the execution chain and stop the unwanted behavior. Second, we develop a Chrome extension compatible with both Manifest Version 2 and Version 3 that enables fast, runtime replacement of refactored code without adding computational cost. Third, we define a rigorous manual evaluation process to assess client-side website functionality after refactoring, ensuring that essential features remain intact.

Impact Summary

This work opened a new line of research that inspired others to examine privacy-invasive JavaScript at function-level granularity, shifting the focus from superficial approaches to the core origins of data collection. [1, 19]. This work was recognized with the *Best Artifact Award* at CCS 2024 [20], underscoring its technical rigor, deployability, and impact in advancing practical privacy-enhancing technologies. Moreover, this line of work has also led to collaboration with Brave, where our refactoring and replacement strategy has been integrated into one of their products, Brave Talk [9].

Current Research

TrackerSift [IMC 2021 and PETS 2023]. My research on JavaScript privacy analysis unifies two complementary efforts, TrackerSift [6] and a follow up study on JavaScript blocking [7]. This line of work was the first to demonstrate that websites intentionally entangle privacy-invasive code within functional code, creating mixed scripts that obscure tracking behavior. TrackerSift addresses the challenge of localizing such mixed code by combining static dependency analysis with dynamic execution tracing to separate legitimate and privacy-invasive functionality across multiple granularities, including domain, hostname, script, and function levels. Building on these insights, the subsequent study introduced a client side breakage analysis framework to examine the trade off between privacy protection and website functionality across different blocking granularities. *Together, these studies revealed that nearly one third of all analyzed JavaScripts exhibit mixed behavior, and longitudinal analysis shows that this proportion continues to increase over time, underscoring the growing complexity of privacy-invasive JavaScript on the modern web.*

Not.js [CCS 2024]. My next work, Not.js [5] addresses the challenge of runtime localization and mitigation by detecting and refactoring privacy-invasive JavaScript during execution without disrupting legitimate functionality. I designed NoT.js as a Chrome-based privacy enhancing extension that deploys lightweight runtime scripts to intercept, analyze, and modify JavaScript behavior. It incorporates a graph-based machine learning model trained on execution traces to distinguish between interleaved privacy-invasive and functional logic. Once identified, Not.js automatically refactors the code by diffusing function calls, isolating the invasive behavior, and replacing it with safe alternatives while preserving overall site functionality. *Evaluated across real world websites, Not.js eliminated 92% of privacy-invasive activity while maintaining 97% of website functionality, reducing JavaScript heap-usage and improving load times with lightweight execution. This work received the Best Artifact Award at CCS 2024 [20], recognizing its real world impact on practical privacy protection.*

Other directions [ICSE 2025 and PETS 2026]. In my most recent work [2], I examined how privacy risks are unevenly distributed across users, particularly among vulnerable groups such as children, elderly users, and individuals who are vulnerable. My paper demonstrates that gestures used by screen readers, such as tabbing, focusing, or hovering, can inadvertently trigger privacy-invasive JavaScript. *We show that vulnerable users were exposed to 1.7x more privacy invasive activity, emphasizing that privacy is not uniform across users and that web design must account for interaction patterns that unintentionally increase exposure.* Another direction I am exploring involves the use of custom headers in collecting and transmitting user identifiers to tracking services. From a JavaScript code perspective, we examine how these identifiers are generated, embedded into custom headers, and subsequently shared with third party tracking entities. This work is currently under submission.

Industry collaborations. I have collaborated with industry partners on projects that offered practical perspectives on large-scale data integrity and privacy challenges. At Amazon Marketplace, I applied my research expertise to a different problem space, developing a framework to detect fraudulent sellers by analyzing behavioral and transactional patterns across large datasets. At Admiral, I worked on classifying and differentiating ad-blockers and on designing strategies to re-serve ads through targeted user engagement prompts.

Future Direction

The next stage of my research focuses on solving the emerging challenges in this field, understanding the barriers that have limited broader engagement, and highlighting why my expertise positions me to address them effectively. In the following section, I describe several projects that exemplify my recent research efforts and outline speculative directions that I aim to explore in the future.

Tracing the provenance of user identifiers on the web. A natural next step in my research focuses on uncovering the end-to-end provenance of user identifiers by tracing how they are generated,

transformed, and ultimately transmitted to tracking entities. Existing tools, including my own, can detect privacy-invasive scripts but lack visibility into the complete lifecycle of these identifiers. My goal is to understand this lifecycle comprehensively, i.e., from the point an identifier is created to when it is exfiltrated, while attributing each stage to the responsible JavaScript code and APIs. To achieve this, the framework constructs execution provenance graphs that integrate taint tracking, symbolic execution, and runtime instrumentation, revealing how identifiers flow through the code with fine grained precision. Building on this foundation, I plan to develop (1) a taxonomy of identifier generation techniques across a large web corpus, (2) a cross layer provenance analyzer that links JavaScript execution traces with network data to pinpoint where and how identifiers are exfiltrated, and (3) a developer assist tool that visualizes provenance chains. Together, these efforts aim to provide the first system level understanding of identifier lifecycles, enabling privacy transparency, accountability, and compliance auditing at scale.

Embedding privacy defenses into the JavaScript engine. A complementary research direction explores detecting and refactoring privacy-invasive JavaScript directly within the V8 engine rather than at the extension layer. Through my work with Brave, which leverages the Chromium-based V8 JavaScript engine, I have gained in depth experience working with its internals i.e., from parsing JavaScript source code into abstract syntax trees to generating bytecode and optimizing it into machine code through TurboFan. Building on this foundation, I plan to embed fine-grained instrumentation hooks at key stages of the V8 execution pipeline to identify privacy-invasive operations such as identifier construction, cross-context data sharing, and network bound serialization. By integrating lightweight static analysis during bytecode generation and applying policy guided transformations at runtime, the system can automatically refactor or neutralize invasive logic before it executes. This approach aims to move privacy protection closer to the engine level, enabling faster, more transparent, and tamper resistant enforcement of privacy rules within the browser itself.

Leveraging large language models for automated privacy repair. Another research direction is the use of large language models (LLMs) to automate the localization and refactoring of privacy invasive JavaScript in a more efficient and context-aware manner. While current approaches in NoT.js rely on symbolic analysis and graph-based learning, LLMs can better generalize across diverse obfuscation patterns and mixed functionalities. The goal of this direction is to train code-aware models such as CodeLlama or DeepSeek Coder on paired datasets of original and refactored JavaScript from NoT.js, enabling them to automatically generate privacy preserving code transformations while maintaining site functionality. This approach aims to achieve near real-time mitigation with minimal human oversight. Future extensions include developing a context guided prompting system using call stack and dataflow summaries, an automated patch verification framework for functional testing, and a feedback loop that refines the model based on runtime validation. Together, these efforts aim to evolve NoT.js into an adaptive, self improving privacy repair system.

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TEACHING STATEMENT

Abdul Haddi Amjad

My teaching and mentoring experiences have provided me with a strong foundation for a career in academia. At Virginia Tech, I served as a teaching assistant for user interface software in Fall 2022 and Fall 2023, where I designed assignments and exams, guided course projects, and led weekly two-hour discussion sessions attended by over 40 students. I also held regular office hours to support students individually, which helped me better understand diverse learning approaches and challenges. In both semesters, my teaching performance was rated **High** (7+ out of 9) by students. In addition, my experience at Educative, an interactive learning platform for software developers, honed my ability to design clear, example-driven technical explanations that make complex programming concepts accessible to a wide audience. Together, these experiences have reinforced my commitment to computer science education and my enthusiasm for mentoring the next generation of researchers.

Teaching Philosophy.

My teaching philosophy is grounded in three principles shaped by my experiences as both a student and a teaching assistant. First, I believe students learn best when they actively shape their learning rather than passively receive information. In user interface software, I implemented a **Propose and Challenge** activity in which students were divided into two teams to evaluate alternative website design options. For example, debating alternative designs for a website’s cookie consent banner, such as prioritizing user privacy by minimizing data collection versus enhancing user experience through personalization. Each group presented arguments for their position, after which we collaboratively listed the pros and cons of each design and discussed trade-offs in usability, transparency, and compliance with privacy regulations. The session concluded with a collective decision on the most balanced design, helping students understand how design and engineering choices directly shape user trust and privacy outcomes.

Second, I emphasize collaborative and two-way learning in the classroom. I frequently used the **Think Pair Share** technique, introduced to me by my Ph.D. advisor Muhammad Ali Gulzar, where students first think about a question individually, then discuss it with a peer, and finally share their responses with the class. For example, in one of my guest lectures on web privacy, I asked students whether blocking all online ads is an ethical and sustainable solution, considering that free content and services often depend on data-driven advertising. Students first noted their individual stance, then discussed with peers the trade-offs between user privacy, free access to information, and platform sustainability. The discussion revealed diverse perspectives and encouraged students to think critically about balancing privacy protection with the economics of the web.

Finally, I actively seek **student feedback** to refine my teaching methods. During the two-hour discussion sessions for user interface software, I initially relied solely on slides to explain key concepts. However, students suggested that using the whiteboard to illustrate design flows and event-handling logic would make the material easier to follow. I incorporated this feedback in subsequent sessions, combining visual explanations on the board with slide-based examples, which led to more interactive discussions and clearer understanding of complex topics.

Mentorship Experience.

I have gained valuable experience from my advisor and collaborators through my first research project. This experience taught me how to structure research effectively by taking small, well-defined steps to validate a hypothesis before moving on to large-scale experiments. I apply the same approach when mentoring students, encouraging them to think critically, set incremental goals, and build confidence through steady progress.

My first mentorship experience was with an undergraduate student, Bless Jah [3], whom I guided on his first research project. I began by introducing the main idea and helping him break it into clear, manageable tasks. Throughout the project, I encouraged open communication and made sure he felt comfortable asking questions and discussing challenges. This mentorship led to tangible research outcomes, including a Best People’s Choice Award for our joint project, co-authorship on research publication [1], and also got featured in VT News [2]. I later helped him prepare for his conference presentation, where he successfully presented our work to an international audience. We have also submitted another incremental work in the same direction that further builds on our initial findings.

I have also mentored a graduate student, Muhammad Danish, who was working with my advisor during his rotation. Since he joined the program after his undergraduate, he was new to academic research and to the field of security and privacy. The first key challenge was to help him build the necessary background and conceptual understanding to engage with ongoing research. Over the course of two consecutive semesters, I guided him through foundational topics while we worked together on a project evaluating privacy perceptions across different user communities. This mentorship ultimately resulted in a publication based on our collaborative work [1].

I am currently mentoring an undergraduate student, Gabriel Pacheco Martinez [4], who has a strong background in cybersecurity and a solid understanding of core privacy concepts. He is leading the research direction on privacy

concerns in HTTP custom headers under my guidance. Together, we first validated our hypothesis that custom headers can be used to collect user identifiers. Gabriel developed the experimental framework under my mentorship and later executed large-scale experiments to test our findings. We held several whiteboard discussions to refine the research narrative, define clear objectives for each experiment, and align them with our research questions. This work has now been completed and is under submission.

Guest-lectures. Additionally, I have had the opportunity to mentor and engage students through invited guest lectures at Washington University in St. Louis (Data-Driven Privacy and Security) and Virginia Tech (Future of Security). In these sessions, I discussed topics such as web tracking defenses, function-level JavaScript blocking, and privacy-preserving program analysis, while guiding students through open research questions and practical challenges in building privacy-enhancing technologies.

Prospective Courses.

I am deeply enthusiastic about teaching both basic and advanced-level courses in Software Engineering and Computer Security and Privacy. At the advanced level, I am particularly interested in developing and teaching courses such as Software Debugging and Testing, Data-Driven Privacy and Security, and Web Privacy, which emphasize hands-on learning, empirical analysis, and the integration of research insights into practical system design. These courses would help students understand how reliability, security, and privacy intersect in modern software systems. At the foundational level, I would enjoy teaching courses such as Introduction to Computer Security, Cybersecurity Fundamentals, and Software Design Patterns, where students learn to design reliable and secure systems from first principles. If needed, I can also teach core courses like Data Structures to help students strengthen their technical foundations. Through this combination of foundational and advanced teaching, I aim to help students develop a holistic understanding of how to design, build, and maintain secure and dependable software systems.

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