Chapter 1

Introduction

The computing infrastructure that underpins today's world is insecure. Code written in unsafe languages (e.g., C) may hide any number of programming bugs that go uncaught until they are exploited in the wild, especially memory errors. Safe or not, any code might contain logic errors (SQL injection, input-sanitization flaws, etc.) that subvert its security requirements.

Although static analyses can detect and mitigate many insecurities, an important line of defense against undetected or unfixable vulnerabilities is runtime enforcement of *security policies* using a reference monitor [1]. In particular, many useful policies can be specified in terms of flow constraints on *metadata tags*, which augment the underlying data with information like type, provenance, ownership, or security classification.

Tag-based policies are well-suited for efficient hardware enforcement, using processor extensions such as ARM MTE [4], STAR [8], and PIPE. PIPE[1] (Processor Interlocks for Policy Enforcement) [5, 6],the specific motivator for this work, is a programmable hardware mechanism that supports monitoring at the granularity of individual instructions. A customizable set of rules updates the metadata tags at key points during execution, maintaining a relationship between the tags and the security-relevant behavior of the system as a whole. If the tags would enter a configuration corresponding to insecure or undesirable behavior, the program *failstops*. PIPE is highly flexible: it supports arbitrary software-defined tag rules over large (word-sized) tags with arbitrary structure, which enables fine-grained policies and composition of multiple policies.

This dissertation centers around the problem of specifying PIPE-style policies. (Although the work is not specific to PIPE, PIPE's basic structure serves to represent the likely capabilities of tag-based enforcement mechanisms in general.) Specification means both the operational definition of how policies work in the concrete sense, and the higher-level formal definitions that capture the kind of security they aim to enforce.

In the literature, PIPE policies are defined at the assembly level. If they aim to enforce source-level constructs, such as memory safety, they do so with the help of compiler annotations; such constructs do not take advantage of the PIPE model's flexibility. If they instead aim to enforce narrower program-specific notions of security, they require careful hand-annotation by an engineer familiar with the source code. Some works have proven or tested their policies against a higher-level security specification, but so far this is restricted to simple specifications and straightforward

[1]Variants of PIPE have been called PUMP [7] or SDMP [10]and marketed commercially under the names Dover CoreGuard and Draper Inherently Secure Processor.

implementations. When policies are optimized to give up some security in the name of performance, it is very hard to specify the security that remains.

The work is divided into three main parts. The first proposes a new formal characterization of stack safety using concepts from language-based security. Though not specific to a PIPE implementation, this formulation is motivated by a particular class of PIPE-based enforcement mechanisms, the "lazy" stack safety policies studied by Roessler and DeHon [10], which permit functions to write into one another's frames but taint the changed locations so that the frame's owner cannot access them. No prior characterization of stack safety captures this style of safety.

Next, I present Tagged C, a *source-level* specification framework that allows engineers to describe policies in terms of familiar C-level concepts. PIPE policies can be difficult for a C engineer to write: their tags and rules are defined in terms of individual machine instructions and ISA-level concepts, and in practice they depend on reverse engineering the behavior of specific compilers. Tagged C takes the form of a variant C language whose semantics are parameterized by tags attached to C functions, variables and data values, and rules triggered at *control points* that correspond to significant execution events, such as function calls, expression evaluation, and pointer-based memory accesses. Tagged C may be seen as an operational specification for instrumenting C with a tag-based reference monitor: it describes policies in terms of their concrete effects on the execution state of the underlying C semantics.

Armed with this knowledge, a Tagged C user may then prove that a given policy enforces a higher-level security specification. In the final third of this dissertation I define a compartmentalization property in the form of a novel abstract compartmentalized semantics, define a Tagged C policy that enforces it, and prove in Coq that the policy satisfies its specification.

1.1 Contributions and Organization

Chapter 2 introduces the concept of tag-based reference monitors and brings the reader up to date on the state-of-the-art in that and related areas. The contributions in this dissertation are divided across its three main topics.

Stack Safety Chapter 3 gives a novel formalization of stack safety in the form of a collection of trace properties. Stack Safety exemplifies the specification problem: "the stack" is not a clearly defined language concept, but a loosely defined component of a system's ABI that is relied on by many different higher-level abstractions. Our trace properties describe the behavior that those abstractions should be able to expect from a well-behaved stack, even when enforced with the optimized "lazy" tagging approach of Roessler and DeHon [10]. Our contributions are:

- A novel characterization of stack safety as a conjunction of security properties—confidentiality and integrity for callee and caller—plus well-bracketed control-flow. The properties are parameterized over a notion of external observation, allowing them to characterize lazy enforcement mechanisms.
- An extension of these core definitions to describe a realistic setting with argument passing on the stack, callee-saves registers, and tail-call elimination. The model is modular enough that adding these features is straightforward.
- Validation of a published enforcement mechanism, *Lazy Tagging and Clearing*, via property-based random testing; we find that it falls short, and propose and validate a fix.

This chapter was first published at the IEEE Computer Security Foundations Symposium, July 2023 as "Formalizing Stack Safety as a Security Policy," a joint work with Roberto Blanco, Leonidas Lampropoulos, Benjamin Pierce, and Andrew Tolmach [3].

Tagged C In Chapter 4, we attack the definition problem by lifting tagged enforcement to the level of C source code. We introduce Tagged C, a C variant whose semantics are parameterized by an arbitrary tag-based policy. The Tagged C semantics and interpreter are based on those of CompCert C [9].

- The design of a comprehensive set of *control points* at which the C language interfaces with a tag-based policy. These expand on prior work by encompassing the full C language while being powerful enough to enable a range of policies even in the presence of C's more challenging constructs (e.g., `goto`, conditional expressions, etc.).
- Tagged C policies enforcing: (1) compartmentalization; (2) memory safety, with realistic memory models that support varying kinds of low-level idioms; and (3) secure information flow.
- A full formal semantic definition for Tagged C, formalized in Coq, describing how the control points interact with programs, and an interpreter, implemented and verified against the semantics in Coq and extracted to OCaml.

The core of this chapter was first published at the International Conference on Runtime Verification, October 2023 as "Flexible Runtime Security Enforcement with Tagged C," a joint work with Andrew Tolmach and Allison Naaktgeboren [2]. Some technical details are also published in Chaak et al. [], a joint work with CHR Chaak and Andrew Tolmach. The original content has been updated to reflect further development, and the chapter has been extended with a detailed discussion of the design decisions that inform the current development.

Compartmentalization Finally, I return to the specification and validation problems, now at the C level. Chapter 5 presents a compartmentalization policy in conjunction with the abstract compartmentalization scheme that it enforces, and proves that the policy indeed enforces the abstract model. In this case the specification takes the form of an abstract machine.

Both the specification and the policy that enforces it are novel, and improve upon the state-of-the art in tag-based compartmentalization by allowing objects to be shared between compartments via passed pointers, without the overhead of protecting every object individually. The proof is mechanized.

- A formal model of C compartmentalization in the form of an abstract machine that supports sharing between compartments while keeping their memories isolated by construction.
- A novel compartmentalization policy for Tagged C that supports cross-compartment sharing with fewer constraints on available tags than similar systems from the literature.
- A proof that the compartmentalization policy is safe with respect to the abstract semantics.

The compartmentalization work is not yet submitted for publication. These topics are split between Chapter 5, which defines the compartmentalization model, and Chapter **??**, which covers the associated policy and the proof effort to show that it enforces that model.

Chapter 2

Tags and Monitors

Chapter 3

Formalizing Stack Safety as a Security Policy

Chapter 4

Flexible Runtime Security Enforcement with Tagged C

Chapter 5

Formalizing Compartmentalization as an Abstract Machine

Chapter 6

Conclusion

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