Security-Driven Compilation:
A New Direction for Compiler Research[*]

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Abstract

The growing importance attached to the security of software systems has focused considerable attention on various problems related to security in computing. A vast array of research efforts ranging from highly technical cryptographic techniques all the way to higher-level information policy are currently engaged in addressing the security needs of the next generation of computing infrastructure. This paper addresses the role that compilers and compiler research can play in this realm. Because they routinely extract useful program structure and transform code, compilers are uniquely positioned in some ways to have a direct impact in the creation of more secure software. These features, among others, together with a fresh approach towards software protection based on compilation, can result in more robust applications and computing infrastructures. This paper will review on-going efforts, explore future research directions and make the case for renewed attention in this important area at the intersection of compiler and security research.

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1 Introduction

Research into *software security* or *software protection* has intensified in recent years following several high-profile disruptions of computing systems. Hackers all over the world know that the key steps to attacking a software system is to first *understand* the software, and then to *tamper* with the software to enable a variety of full-blown attacks. The growing area of software protection aims to address the problems of *code understanding* and *code tampering* along with related problems such as *authorization*. The general objective of research efforts in this area is to provide techniques to help proper authorization of users, to prevent code from being tampered with and to also make it harder for attackers to extract information that could be used in identifying system vulnerabilities. Computer security has witnessed several decades of research that has produced techniques in a variety of security-related areas including among others: cryptography, security protocols, proof systems, intrusion detection, authentication, policy definition and enforcement, secure communication, and architectural support for secure computing. Over time, security objectives have invited cross-disciplinary interest as researchers in theory, networking, architecture, data mining and signal processing, have brought their expertise towards addressing problems in security.

The purpose of this paper is to address the following question: what role can compilers and compiler research play in achieving security objectives? By reviewing current efforts in this area, and outlining potential directions for future research, we make the case that the research community can benefit from a greater level of attention directed at the intersec-

tion of compilers and security. Just as compiler and language research has evolved over the years to encompass objectives such as parallelism, interpreted languages, virtual machines, architecture and hardware description languages, so too, we argue, should compilers take up security as a primary objective.

Our belief in the stronger role that compilers should play in future secure systems is based on the following rationale: First, compilers are well-positioned in their "gateway" role in software creation: almost all executable software today is created with compilers, and therefore, effective techniques embedded in a compiler can automatically reach executables without conscious effort on the part of developers. Second, compilers already extract a great deal of program structure, enabling a more detailed automated analysis than may be possible with pre or post-compilation tools. Third, compilers modify code in various ways; these transformations can be used for many security objectives. In fact, this key feature is part of the foundation of many existing software protection approaches. Fourth, because decades of research in compiler optimization have made their way into compiler infrastructures, the compiler is probably the best place to manage security-performance trade-offs. Fifth, many well-known compilers such as `gcc` centralize architectural information in one place and therefore, security transformations that are implemented at the level of intermediate code or higher can immediately impact code written for a variety of processors. Sixth, compilers often exploit architectural features such as instruction-level parallelism and are therefore well-positioned to exploit similar hardware support for security. Finally, and perhaps most importantly, because compiler research involves managing entire compiler infrastructures, compiler researchers tend to be experienced in all aspects of compilers, ranging from language constructs at the front-end to low-level hardware features at the back-end. This encourages a comprehensive top-down view in supporting security objectives.

In this paper, we review on-going efforts in many sub-areas of compiler-security research. These include high-level language design issues as well as low-level hardware issues. Because compiler research includes this broad span of issues, there are equally many promising directions for future research.

To help frame our discussion of issues, we divide attacks on software integrity into four kinds. In a *code tampering attack*, executable code is tampered with for a variety of purposes including interfering with licensing, changing the feature-set and using the code to attack other devices. A typical example is the well-known buffer-overflow attack on the networking stack. An *authorization attack* is when code tampering is used to circumvent a vendor's checking of permission in executing software on a particular hardware. A *data tampering attack* refers to modifications of data such as passwords or internet addresses to enable hackers to exert control of software behavior. Finally, the term *code understanding* is self-explanatory: it is the necessary first step to any of the other attacks.

The remainder of this paper is organized as follows. In Section 2, we describe past and on-going work in the field of software protection, categorizing them in various areas that we hope will be helpful to the reader. We follow that in Section 3 by describing a few projects in a little more detail, especially focusing on projects that we are most familiar with. Finally, Section 4 speculates on future directions.

2 Related Areas of Research

In this section, we review past and current work in the general area of software security as related to compilers. A broad survey of several software protection techniques appears in [25]; these range from tamper resistant packaging to hardware copyright notices. A survey of the broader area of software security in the context of DRM appears in [10, 62]. Note that several companies have formed the so-called Trusted Computing Platform Alliance (TPCA) to provide hardware-software solutions for software protection [67]. Finally, an excellent survey of tools for open-source software is provided in [16], with a summary of analysis tools (some of which involve source code parsing) as well as runtime tools (such as StackGuard) that can be broadly considered in the area of languages and compilers. Our review will therefore focus on projects that also feature code

generation.

2.1 Copyright notice and Watermarking

The oldest "prevention" technique is to embed a copyright notice into the code and to check for the existence of the copyright upon execution. Because an ordinary insertion of text is easy to find, compiler techniques can be used to generate a number of ingenious watermarks by transforming the code. For example, the arrangement pattern of basic blocks or the order of functions in memory can be used to encode a unique pattern that is hard to discern. A survey and taxonomy of watermarking techniques can be found in [13, 14].

Watermarks are very useful in tracking and identifying code that may be illegally copied because unique watermarks can be used to trace the original owner. However, they cannot prevent attacks during execution unless accompanied by code that periodically checks for the presence of the watermarks. Note also that this form of software protection is probably the easiest to hack: the code that checks is simply removed or routed around. Also, a copyright check even if valid does not prevent a hacker from actually modifying the code for unauthorized purposes.

2.2 Obfuscating Compilers

In this technique, now receiving much attention, code is deliberately mangled while maintaining correctness to make understanding difficult – a survey of obfuscation techniques appears in [12]. Obfuscation techniques range from simple encoding of constants to more complex ones that re-arrange or transform code [11, 12]. Techniques in [57, 58] also propose transformations to the code that make it difficult to determine the control flow graph of the program, and show that determining the control flow graph of the transformed code is NP-hard. Theoretical limitations are discussed in [6]. Obfuscation is attractive because it is simple to use, does not involve any keys and addresses the code understanding problem. It can be used in conjunction with other techniques that address code tampering. Obfuscation can also simultaneously provide a watermark. However, many obfuscation techniques can be attacked by designing tools that automatically look for obfuscations. Another approach to attacking obfuscation techniques is to run the code in a debugger and to identify vulnerabilities by stepping through the code in the debugger.

2.3 Compiler-Generated Signatures

A *digital signature* [51] is a standard cryptographic technique to help identify whether a block of text has been modified. Typically, a text is hashed to form a digest and the digest is signed with a key. Then, any attack that modifies the text can be detected since the modified text will result in a different digest with extremely high probability. Often, the hash is simply a checksum, an idea that has been exploited for computing digests of executable code.

The work in [8] introduces the concept of *guards*, pieces of executable code that perform checksums to guard against tampering. In [29], the authors propose a dynamic self-checking technique to improve tamper resistance. The technique consists of a collection of "testers" that test for changes in the executable code as it is running and reports modifications. A tester computes a hash of a contiguous section of the code region and compares the computed hash value to the correct value. An incorrect value triggers the response mechanism. They note that the performance is invariant until the code size being tested exceeds the size of the L2 cache, and a marked deterioration in performance was observed when this occured. The techniques in [8, 29] are compatible with copy-specific watermarking and other tamper resistant techniques and requires using these to provide a high level of software protection. In [4] a self-checking technique is presented in which embedded code segments verify integrity of the program during runtime. The above proposed "self-checking" approaches essentially compute checksums on code to assert code integrity [8, 29]. This computation is exactly the same as any other digest or MAC computation for secure communication: it relies on the high probability that a modification to the code will create a modified checksum.

Such digest checking is attractive because digests can detect any kind of modification to code or data, and is relatively inexpensive in terms of computation

effort. Furthermore, no keys are required if the digests are well-hidden. At the same time, these techniques strongly rely on the security of the checksum computation itself. If these checksum computations are discovered by the attacker, they are easily disabled. However, in many system architectures, it is relatively easy to build an automated tool to reveal such checksum-computations. For example, a control-flow graph separates instructions from data even when data is interspersed with instructions; then, checksum computations can be identified by finding code that operates on code (using instructions as data). This problem is acknowledged but not addressed in [29].

2.4 Static Analysis and Runtime Support

Static code analyzers scan source code and alert the programmer about problems that might be exploited for attacks. An excellent survey of tools, both static analyzers as well as those with runtime complements, is provided in [16]. Static analysis tools such as BOON [56] and CQual [26] scan C source code to find potential buffer overflows or inconsistent usage of values. MOPS [9] uses a finite state machine model of of what is considered valid behavior for a particular program. If a property is violated during analysis, *i.e.,* an illegal state is reached in the finite-state automaton, the programmer is alerted about a potential vulnerability.

Static analysis is often complemented by runtime support. This idea is not new – languages that enforce array bound checking have existed since the early days of computing. However, what is new is that these ideas can be carried over into languages like C with the help of tools such as StackGuard [55] (to ensure that return addresses are valid) and FormatGuard [17] (to address attacks on C's printf function). While static and runtime analysis are focused on particular types of attacks, the general idea of ensuring correct behavior can be made stronger by guaranteeing properties, as we discuss next.

2.5 Proof Carrying Code

Proof-Carrying Code (PCC) is a technique by which a host can verify code from an untrusted source [38, 40, 41, 2, 5, 7]. Safety rules, as part of a theorem-proving technique, are used on the host as guarantees for proper program behavior. Applications include browser code (applets) [5] and even operating systems [38]. PCC is attractive for several reasons. One advantage of proof-carrying software is that the programs are self-certifying, independent of encryption or obscurity. A second advantage is that one can formally assert properties and state guarantees. There is ongoing work on providing a compiler that can build proofs automatically during compilation. The PCC method is essentially a self-checking mechanism and is vulnerable to the same problems that arise with the code checksum methods discussed earlier; in addition they are static methods and do not address changes to the code after instantiation.

2.6 Programming Languages

A compelling approach to incorporating security into software is to force the issue at the early development stages, into a programming language itself or in tools that rewrite programs to achieve security objectives. Several efforts [31, 34, 39, 45] have taken up this approach, resulting in techniques that use type-safe assembly [37], language modification [31, 39] or reference monitors [23, 45]. Comprehensive surveys of the general approach can be found in [34, 45].

A reference monitor is a piece of software, sometimes with hardware support, that observes the execution of a program to see whether memory bounds or forbidden accesses are violated. Such monitoring capability may be incorporated into a trusted operating system or may be "in-lined" into existing compiled code [23]. The paradigm of typed intermediate languages [27, 28] provides for type information to be maintained and verified through the backend of the compilation process [28, 37]. A type-checker then verifies type safety, allowing programmer errors as well as tool-chain errors to be caught. This approach, similar to the proof-carrying code concept described earlier, is taken a step further in the notion of a certifying compiler. For example, the Java compiler can be said to certify that it produces type-safe bytecode, some properties of which are checked at load time by the JVM. Language-based approaches also include formal language methods, such as the

extension of pi-calculus for security [1].

These approaches form a useful complement to the compiler-based approaches described thus far. Language-based approaches go a step further in security by attacking the general problem of correctness and incorporating safeguards against programmer errors. At the same time, direct modifications to a language require a buy-in from the community and may take time to find their way into standards. The long-term impact of language-based approaches is that useful features often find acceptance in the next generation of languages, as Java has shown.

2.7 Compiling for Cryptographic Architectures

We now describe some custom hardware approaches to software protection because their relevance in terms of compilers is that code generation is usually followed by encryption, a feature that can be considered a back-end compiler function.

In a secure coprocessor, programs can be run in an encrypted form on these devices thus never revealing the code in untrusted main memory memory and thereby making it difficult to understand or tamper with. A number of secure coprocessing solutions have been designed and proposed, including systems such as IBM's Citadel[43], Dyad [53, 63, 64], the Abyss and μAbyss systems [61, 60, 59], and the commercially available IBM 4758 which meets the FIPS 140-1 Level 4 validation [30, 49, 50]. An alternative to a co-processor is a processor that is designed to directly execute encrypted code, such as the architecture proposed in [35], in which an execute-only memory (XOM) allows instructions stored in memory to be executed but not manipulated.

Like a custom processor, a custom operating system on a standard processor presents an alternative approach to software security. However, they are expensive to build and maintain. A more promising approach might be an operating system such as SE-Linux [36] with features that enable customizable security.

FPGA's have been used for security applications mainly for the purpose of speeding up cryptographic computations [19, 44, 52, 33]. The FPGA manufac-

turer Actel [15] offers commercial IP cores for implementations of the DES, 3DES, and AES cryptographic algorithms and is currently developing new anti-fuse technologies that would make FPGAs more difficult to reverse-engineer [20].

2.8 Joint Compiler-Hardware Approaches

The hardware solutions described above that operate on fully-encrypted executables are attractive because of the quality of security they are able to provide. At the same time, they require a substantial buy-in from hardware manufacturers and can considerably slowdown execution speed.

Such a highly-secure hardware approach and the obfuscation techniques described earlier together form two ends of a security-performance spectrum. At one end are the hardware schemes that are either slower or require special purpose processors, and at the other end are obfuscation like schemes that are efficient but provide limited security. These extremes invite an approach that allows system designers to position themselves where they choose on the security-performance spectrum.

In [65, 66] we describe a joint compiler-hardware approach that is designed to allow systems to be positioned at various points in the spectrum. The hardware used is an FPGA (Field Programmable Gate Array), which offers field-programmability and is readily available with many processor cores. This approach is described next in Section 3.1.

3 Some Current Projects

3.1 SAFEOPS - A Joint Compiler/Hardware Approach

SAFEOPS (Software/Architecture Framework for the Efficient Operation of Protected Software) [65, 66] is a compiler/FPGA technique in which the processor is supplemented with an FPGA-based *secure hardware component* that is capable of fast decryption and, more importantly, capable of recognizing and certifying strings of "codes" (keys) hidden in regular unencrypted instructions - see Figure 1. Parts of executable code are either fully

Executable Program

Encrypted portions

Hidden code in instructions

A

Unencrypted but with embedded codes

d

A′

Instruction at offset d

Main Memory

L2 Cache

System Bus

I$

L1 Cache

D$

Processor Core

Other resrcs:
- DSPs
- FPGAs
- ASICs
- RAMs
- etc.

FPGA

Validation Cache

Instruction Filters

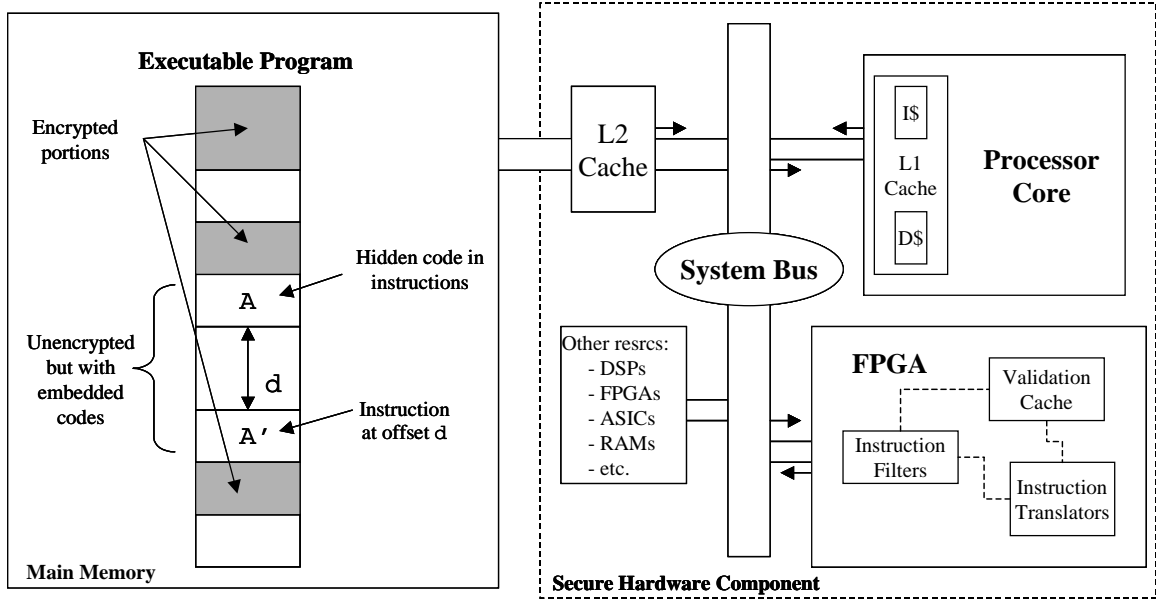Instruction Translators

Secure Hardware Component

Figure 1: Conceptual view

encrypted with standard private-key techniques [18] or contain embedded keys. The fully encrypted segments are decrypted by the FPGA. The segments containing embedded keys are processed by the FPGA before they reach the L2 cache, allowing the FPGA to examine the veracity of the keys. For example Figure 1 shows that the first part of the executable is encrypted whereas the second part of the executable shows a hidden code A and, at a distance d from A, an instruction A'. Upon recognizing A, the FPGA will expect $A' = f(A)$ at distance d (where f is computed inside the FPGA); if the executable is tampered with, this match is highly unlikely to occur and the FPGA will halt the processor. The code sequences are hidden within both within instructions and data.

One way to embed codes through compilation is to use the register allocator, since register assignment presents some degrees of freedom. Consider a sequence of instructions comprising the instruction stream that use registers. If we focus on, say, the first register in each register-based instruction, the resulting sequence of registers so used in the instruction stream is called the *register stream.*

The key observation is that this register stream is determined by the register allocation module of the compiler. In the FPGA hardware, the register stream can extracted from the instruction stream, in addition to other information such as particular opcodes of interest in the embedding mechanism.

Suppose we use register R_1 to encode '0' and R_2 to encode '1.' Then, the particular sequence of registers $R_1, R_2, R_2, R_1, R_1, R_2$ corresponds to the key **0 1 1 0 0 1**. This key is then compared against a cryptographic function of the opcode stream in the FPGA.

Thus, in the general technique, the compiler performs instruction filtering to decide which instructions in opcode stream will be used for checking. The compiler then uses the flexibility of register allocation to bury a key sequence in the register stream. Upon execution, the entire instruction stream is piped through the secure FPGA component, which is set up to recognize the particular register stream of interest. The FPGA then extracts both the filtered opcodes and the register sequences for comparisons. If a violation is detected, the FPGA halts the processor. If the code has been tampered with, there is a very high probability that the register sequence will be destroyed or that the opcode filtering will pick out a different instruction.

As described in [65, 66], the technique can be

6

applied to in its simplest form to small embedded processors with FPGA cores that have little capability for full encryption. More importantly, the register allocation is a proper register allocation so that the executables can run on processors that don't feature a policing FPGA. Finally, by using private keys in the FPGA, a higher level of security can be achieved by using the private key against the stream along with cryptographic hashing. These techniques together with the compiler's ability to extract program structure and perform register allocation provide the means for controlling the security-performance tradeoff, a key goal of the project.

3.2 CODESSEAL - Key Management for Encrypted Execution

CODESSEAL (COmpiler DEvelopment Suite for SEcure AppLications) [42] is a project focused on joint compiler/hardware techniques for fully encrypted execution, in which the program and data are always in encrypted form in memory. This technique involves the use of an FPGA placed between main memory and the cache that its closest to main memory (L1 or L2, depending on the system). The instructions and data are loaded into the FPGA in blocks and decrypted by keys that are exclusive to the FPGA. Thus, the decrypted code and data are visible "below" the FPGA, typically inside a chip, thereby preventing an attack that sniffs the address/data lines between processor and memory. The original code and data are encrypted by a compiler that uses the same keys. The assumption is that both FPGA loading and compilation occur at a safe site prior to system operation.

Note that FPGA's can be used to detect code tampering even when full encryption is not used. A simple approach, in this case, is to compute hashes of instruction code blocks. For example, instructions block hashes using SHA-1 are maintained inside the FPGA, and as each instruction block is loaded, the SHA-1 hash is computed in the FPGA. If the hash does not match the stored hash, tampering is assumed and the processor is halted. Even when full encryption is used, it is desirable to perform a hash check because a tampering attack can be used to disrupt execution without decryption.

Data tampering is more complicated because a write operation necessitates a change in the encryption: data needs to be re-encrypted on write-back to RAM. Also, because data can get significantly larger than code, a large set of keys might be needed to encrypt data, resulting in a key management problem. We propose the following approach to key management. Blocks of keys are themselves encrypted with a small subset of master keys and stored in RAM. When a data block is brought into the FPGA for decryption, the start address is used as a hash to identify its key block, following which the key block is loaded from memory if required. The key is then retrieved and the data block is decrypted. Upon write-back, the block is re-encrypted and written to main memory. For new data blocks, a fresh key may need to be generated, with its key block re-written to main memory.

4 Future Research Directions

In this section, we briefly identify future research directions in the area we have termed security-driven compilation:

- *Integrated approaches*. Clearly, it is desirable to combine the simple efficiency of obfuscation and checksum methods with hardware approaches. Integrated approaches also have gthe advantage of creating executables that flexibly execute on both on processors with supporting security hardware as well as those without.

- *Security-performance tradeoffs*. While the performance impact of individual techniques have been studied [8, 29, 35, 65], future compilers should provide system designers with features that allow explicit tradeoff between security and performance that go beyond key length. For example, a combination of partial encryption and checksum-checking may suffice in providing a wide range of execution performance. Indeed, very little is known today about the relative interplay betwween standard compiler optimizations and security-driven code transformations.

- *Attacks on encrypted execution*. Just because executables are encrypted in main memory dur-

ing execution doesn't mean attacks cannot be effective. Several types of replay, data and structural attacks are possible that a resourceful attacker can use to systematically uncover particular behaviors. We term such attacks as EED attacks – attacks on *Encrypted Executables and Data*. To help detect such attacks, compilers will need to play a key role in extracting structural information for use by supporting hardware.

- *Joint Compiler/OS approaches*. A secure or trusted operating system provides an infrastructure that may be more flexible than hardware and have broader impact so that files and storage may be included in security guarantees. Thus, for example, compiler-generated keys can be used in file read and write operations to secure files.

- *Secure tool-chains*. As mentioned in the Introduction, compilers have the potential of incorporating security in large numbers of systems because of their unique role in the creation of software. Similarly, one can conceive of incorporating security as a major design objective in the entire tool chain for computing infrastructures. A deeper issue arises from asking the question: how can a tool-chain itself provide guarantees? Trusted tool-chains may form the first line of defense prior to system operation.

- *Hardware/Software co-design*. Just as hardware/software co-design is today becoming the prevalent approach to designing systems, so should this approach prove valuable in designing trusted systems. The design of supporting hardware will depend on the software application, and likewise, compiler optimizations will depend on supporting hardware.

5 Summary

This paper has surveyed several projects in the rich and growing intersection between compilers and security. We have argued that compilers are especially well-suited to addressing many problems in software

protection and that compiler research in this area can extend in many promising new directions.

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9

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