

C Annotations for Concurrent Information Flow Security

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June 2021

Abstract - Information flow security in concurrency is difficult due to the increasing complexity introduced with multiple threads. Additionally, compiler optimisations can break security guarantees that have been verified in source code. In this paper, we propose a thesis to explore these issues through providing annotations in C source code that propagate through to the binary or assembly. These annotations could then be used to guide a static analysis of information flow security in concurrency. This approach involves (1) capturing C source code annotations provided by the user about the security policy of data and variables and (2) passing these annotations down to lower representations where static analysis tools can be utilised to identify security vulnerabilities in the produced binary.

1 Topic Definition

This paper describes the motivation, background knowledge and plan for the proposed thesis *Compiler Annotation Solutions for Concurrent Information Flow Security*.

There is a high degree of complexity in verifying security guarantees in concurrent programs [19][27][29]. Additionally, aggressive compiler optimisations can modify the binary output in unexpected ways [7]. To preserve the security of a program, the flow of sensitive information must be protected to avoid flowing in to untrusted sources [2]. This is where static analysis tools can be used to verify the integrity of security guarantees and the flow of sensitive information. In this thesis, we look

to explore a solution to information flow security in concurrent programs through analysing the output after aggressive compiler optimisations.

We propose a tool to analyse C programs to detect security violations in information flow control. This tool will preserve annotations provided by the programmer in source code through lowering passes and aggressive compiler optimisations. The tool will work alongside the *Weakest Precondition for Information Flow* (wpif) transformer described by Winter et al. [31] to allow the programmer to assess the security of information flow in their concurrent programs.

Similar tools for propagating annotations and properties through compiler optimisations have been explored [30] [25] [18], however, these tools focus on either generic solutions for propagating properties or to assist the static analysis of the *Worst Case Execution Time*.

2 Background

Vulnerabilities in software can lead to catastrophic consequences when manipulated by attackers. In an open-source cryptographic software library (OpenSSL) used by an estimated two-thirds of web servers [16] a security flaw called Heartbleed was discovered. Secure secrets such as financial data, encryption keys, or anything else stored in the server's memory could be leaked. Normally, one would send a Heartbeat request with a text string payload and the length of the payload. For example, a message of "hello" could be sent with the length of the message, 5. However, due to a improper input validation (buffer over-read), one could send a length longer

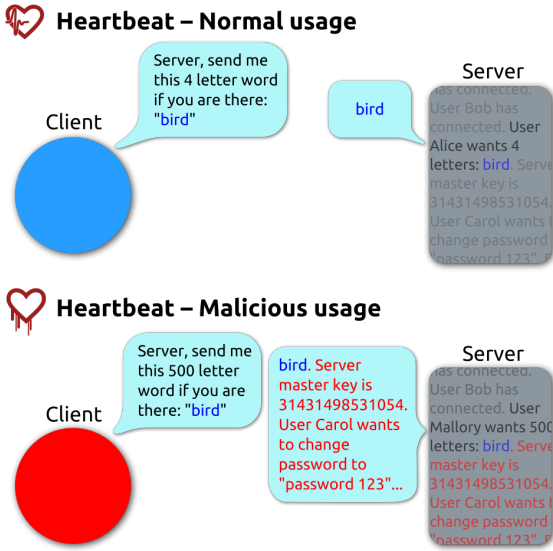


Figure 1: The Heartbleed bug. [13]

that the string they actually sent. This would cause the server to respond with the original message and anything that was in the allocated memory at the time, including any potentially sensitive information. An example of this is shown in figure 1 [13].

Heartbleed was one of the most dangerous security bugs ever, and calls for major reflection by everyone in industry and research [2].

2.1 Information Security

Computer security is defined as a preservation of **integrity, availability and confidentiality** of information, and extends to include not only software but hardware, firmware, information, data and telecommunications [15]. Confidentiality requires that data is not available to unauthorised users, and that individuals can control what information can be collected and disclosed to others. Data integrity requires that only authorised sources can modify data, and that the system can perform tasks without interference from outside sources. Finally, availability of a system requires that service is not denied to au-

thorised users. Together, these principles create the CIA triad [28]. To enforce a secure system, all three principles must be upheld.

Modern programs are becoming increasingly complex with potential for networking, multi-threading and storage permissions and more. As such, security mechanisms must be put in place to verify and enforce the information security requirements. The adequacy of a security mechanism depends on the adversary model. The adversary model is a formal definition of the attacker and their abilities in a system, and defines who we are protecting against [10]. Ideally we would like to design a system to protect against the strongest adversary or attacker, however, this is often not required or even possible. Instead, we must consider the security policy, security mechanism and strongest adversary model to make a system secure [2].

Standard security processes that handle access control such as a firewall or antivirus software can fail as they do not constrain where information is allowed to flow, meaning that once access is granted it can propagate to insecure processes where it can be accessed by attackers. Where a large system is being used, it is often the case that not all components of the codebase can be trusted, often containing potentially malicious code [24]. Take for example your modern-day web project. Where a package manager such as Node Package Manager (npm) could be used to utilise open-source packages to speed up development progress, it could also inadvertently introduce security vulnerabilities. Rewriting all packages used to ensure security would be time-consuming and expensive and is not a viable option. Instead, controlling where information can flow and preventing secure data from flowing into untrusted sources or packages can maintain confidentiality of a system.

One may suggest runtime monitoring the flow of data to prevent leakage of secure data. Aside from the obvious computational and memory overhead, this method can have its own issues. Although it can detect an *explicit* flow of data from a secure variable to a public variable, it is unable to detect *implicit* data flow, where the state of secure data can be inferred from the state of public data or a public variable [9]. Take for example figure 2. In this example,

```

1 secret := 0xC0DE mod 2
2 public := 1
3 if secret = 1
4     public := 0
5

```

Figure 2: Implicit flow of data to a public variable

a public, readable variable is initially set to the value of 1. There is also a secret variable which may contain a key, password or some other secret that must be kept secure from any attackers. Depending on the value of the secret variable an attacker can infer information about this variable depending on whether the value of the public variable is updated to a value of 0. Assuming that the inner workings of the system is known by the attacker, information about the secret variable can be leaked *implicitly* and inferred by the state of public variables.

Security concerns do not only exist at the application level. In a huge codebase such as an OS, different low-level bugs can be exploited to gain access to data, such as by using buffer overflows to inject viruses or trojans [1].

2.2 Information Flow Control

As seen by the issues that can be introduced via implicit and explicit flow of data, there is room to improve on the existing techniques imposed by current security measures. To protect confidentiality, secure or sensitive information must be prevented from flowing into public or insecure variables. Additionally, to protect integrity, untrusted data from public sources must be prevented from flowing into secure or trusted destinations [2]. An information flow security policy can be introduced to classify or label data, or more formally, a set of *security levels* to which each object is bound by across a multi-level security lattice [8]. In this thesis, we will focus primarily on preserving confidentiality.

Many security levels can be identified to classify different classes of objects, however, for now we will consider two security levels: high and low. Data labelled as high signifies that the data is secret, and

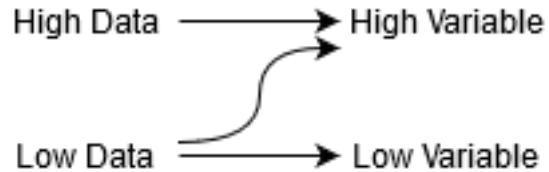


Figure 3: Permitted flow of data

low data is classified as non-sensitive data, such that it does not need to be protected from an attacker or adversary. Variables that can hold data in a program can additionally be classified as high or low as a *security classification*. A variable's security classification shows the highest classification of data it can safely contain [31]. A high variable can hold both high and low data, whereas a low variable which is visible to an attacker can only safely hold low data. As mentioned previously, confidentiality must be upheld by preventing high or secret data from flowing to low or public variables where an attacker can observe it. The permitted flow of data can be observed in 3. Note that high data is not allowed to flow into low variables.

2.3 Information Flow Security in Concurrency

Controlling the flow of information is a difficult problem, however, this is only exacerbated in concurrent programs, which are a well known source of security issues [19][27][29]. Research has been conducted into concurrent programs to explore ways the security of concurrent programs can be verified. Mantel et al. [20] introduced the concept of assumption and guarantee conditions, where assumptions are made about how concurrent threads access shared memory and guarantees are made about how an individual thread access shared memory that other threads may rely upon. Each thread can be observed individually using assumptions over the environment behaviour of other threads that can be then used to prove a guarantee about that individual thread. As two concurrent threads can interleave their steps and behaviour, there is a lot of complexity and pos-

sibilities for the overall behaviour. This concept of assumptions (or rely) and guarantee conditions can reduce the complexity of understanding interleaving behaviour in threads and assist in verifying the correctness of information flow security in concurrency. However, this approach is limited in the types of assumptions and guarantees it supports. Building on this, Murray et al. [12] [21] provide information flow logic on how to handle dynamic, value-dependent security levels in concurrent programs. In this case, the security level of a particular variable may depend on one or more other variables in the program. As such, the variable’s security level can change as the state of the program changes. This logic is essential where the security level of data depends on its source. However, this approach is not sufficient when analysing non-blocking programs. The approach relies heavily on locks which block particular threads from executing. This in turn leads to slower processing due to blocked threads [23].

To overcome information flow security in non-blocking concurrent threads, Winter et al. [31] explores verifying security properties such as non-interference through the use of general rely/guarantee conditions using backwards, weakest precondition reasoning. Such an analysis would additionally handle implicit flows as shown in figure 3. Ideally a tool could be created to verify security policies required for sensitive processes. Users of this system could provide rely/guarantee conditions for each thread as well as security levels for data and variables i.e. high or low data and variables. Working backwards through the execution of the program, violations of the security policy will be detected. Detected violations could be due to an incorrect assumption of the rely and guarantee conditions or a failure to uphold the security policy. This thesis will focus on the compilation stage of this tool.

2.4 Compilers and Security

Compilers are well known to be a weak link between source code and the hardware executing it. Source code that has been verified to provide a security guarantee, potentially using formal techniques, may not hold those security guarantees when being ex-

```

1 crypt() {
2     key := 0xCODE // Read key
3     ... // Work with the key
4     key := 0x0 // Clear memory
5 }
6

```

Figure 4: Implicit flow of data to a public variable [7]

ecuted. This is caused by compiler optimisations that may be technically correct, however, a compiler has no notion of timing behaviour or on the expected state of memory after executing a statement [7]. This problem is known as the *correctness security gap*. One example of the correctness security gap is caused by an optimisation called dead store elimination. Figure 4 was derived from CWE-14 [6] and CWE-733 [5] and used by D’Silva et al. [7]. Here a secret key was retrieved and stored in a local variable to perform some work. After completing the work, and to prevent sensitive data from flowing into untrusted sources, the key is wiped from memory by assigning it the value 0x0.

From the perspective of the source code, a programmer would expect the sensitive data from key to be scrubbed after exiting the function. However, key is a variable local to the function. As key is not read after exiting the function, the statement that assigns key to a value of 0x0 will be removed as part of dead store elimination. This results in lingering memory that could be exploited by an attacker. In GCC, with compiler optimisations on, dead store elimination is performed by default [22]. Additionally, dead store elimination has been proven to be functionally correct [3][17].

This leads to the question, *what security guarantees in source code are being violated by compiler optimisations?* Although one could analyse each individual compiler optimisation to check for potential security violations in source code, defensively programming against the compiler can be counter-initiative. Additionally, compilers are getting better at optimising away tricks programmers write to work against the compiler, and thus is not a future-proof

solution [26]. One might also suggest turning compiler optimisations off, however, this leads to slower code. In a concurrent system where execution time is critical, turning compiler optimisations off is not a viable option. Instead an alternative solution is to perform a static analysis on binary or assembly for security violations. As compilation has already been executed, such analysis would reveal security guarantee violations that result due to compiler optimisations.

2.5 Annotations

This project can take two routes; the proposed tool will be required to run an analysis on either binary or assembly. For either route, annotations used to guide a static security analysis will need to be provided by the user in the C programs they write. The tool will then be required to propagate these annotations down to compiled forms, i.e. binary or assembly. From here, a static analysis can be conducted as described by Winter et al. [31]. Ideally these annotations can be propagated through with little to no modification of the C Compiler being used as to reduce complexity and increase modularity and reusability of such a tool. However, it is unclear as to whether passing annotations down with no modification to the compiler is currently possible. In this thesis, this issue will be explored.

Running a static analysis on a binary can be difficult due to the low level nature of a binary file. As such, to sufficiently perform such an analysis, the binary would be required to be decompiled to a higher-level form, such as an assembly file. From here a static analysis could be conducted. The alternative approach would be to perform the analysis directly on the compiled assembly output files rather than reducing these to binary. Currently, it is unclear as to what compiler optimisations are made when reducing an assembly file to binary, and will be explored further throughout the lifetime of this thesis. The flow of information can be viewed in Figure 5, where formats a static analysis can be performed are outlined in a dashed line. In GCC, “temporary” intermediate files can be stored using the flag *save-temps* [14]. These stored files can then be used for analysis.

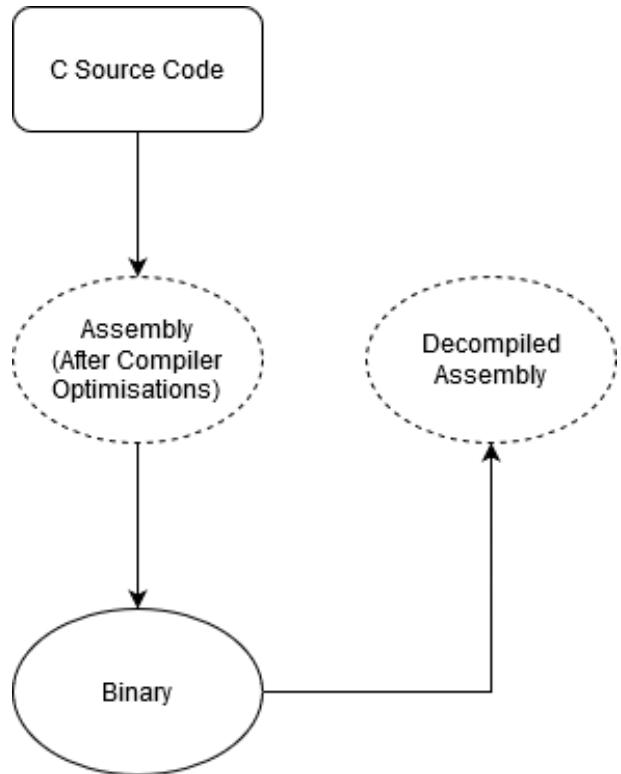


Figure 5: The static analysis options after compilation.

2.6 Related Work

In safety-critical real-time software such as flight control systems, it is required to analyse the *Worst Case Execution Time* (WCET). This kind of analysis can be conducted using static analysis tools to estimate safe upper bounds. In the case of AbsInt’s aiT tool this analysis is conducted alongside compiler annotations to assist where loop bounds cannot be computed statically. In these cases, the user can provide annotations to guide the analysis tools [25]. This tool builds on an existing annotation mechanism that exist in CompCert, a C compiler that has been formally verified for use in life-critical and mission-critical software [4][18]. CompCert annotations are not limited to WCET analysis. A general mechanism for attaching free-form annotations that propagate through to assembly files can be achieved with CompCert. This approach is able to reliably transmit compiler annotations through to binary through method calls which are carried through compilation and the linked executable without using external annotation files. CompCert prints annotation strings as a comment in the generated assembly code, and an additional tool is used to parse these comments and generate annotations. However, due to its treatment as an external function, annotations cannot be placed at the top level of a compilation unit, unlike a variable declaration. Compiler optimisations can additionally cause further issues when trying to preserve annotations through compilation. If dead code is eliminated, annotations associated with that code can be lost as well. Extra care needs to be taken to avoid these optimisations destroying links between properties and the code they refer to during such transformations.

TODO: Include further documentation on how to use Compiler & inline assembly

A similar approach to CompCert is used by The ENTRA (Whole-Systems ENergy TRANsparency). As part of providing a common assertion language, pragmas are used to propagate information through to comments in the assembler files. Information is retained in LLVM IR and ISA representations. However, these annotations are not stored in the final binary and thus comments must be extracted from

assembler files [11].

Vu et al. [30] explore capturing and propagating properties from the source code level through lowering passes and intermediate representations. Their goal was to maintain these properties to binary through aggressive compiler optimisations. As compilers only care about functional correctness, they have no notion of the link between properties and the code it refers to. Thus, there is no way to constrain transformations to preserve this link or to update these properties after the transformation. As such, they approached the problem to create a generic solution, modifying a LLVM compiler with virtually no optimisation changes. This was done by creating a library in LLVM. The properties were stored in strings, and these strings were parsed to build a list of observed variables and memory location. A LLVM pass was inserted to store all these properties in metadata. After each optimisation pass, a verification pass was inserted to check the presence of metadata representing the properties, variables and memory locations. If an optimisation pass had caused the verification to fail the programmer would then be notified, to which they could annotate differently or disable the optimisation.

3 Approach

The approach was set out by first analysing existing methods of preserving annotations through intermediate representations. These include the:

- compCert Verified C Compiler,
- GNU Extension for Extended Inline Assembly, and
- Modifying the LLVM compiler to preserve annotations throughout intermediate representations.

Each of these approaches will be analysed individually for viability across each of the test cases outlined in section 3.1. For approaches that pass all necessary test cases, a further analysis will be conducted into its suitability and development of any necessary tools to assist in the preservation technique, as outlined in sections 3.2 and 3.4. Finally, an analysis on the runtime efficiency of the program will be conducted to assess the success of the annotations with various levels of optimisation. The approach for this analysis is outlined in 3.3.

3.1 Test Cases

A suite of test C programs (See Appendix A) were created to assist in guiding the process of evaluating each approach as a possible means of preserving annotations. Each program has inline comments documenting the annotation that should be preserved and its location within the program. Additionally, each program aims to test a separate element required to perform a static wpif analysis. Namely, these are to preserve the following through to the assembly output:

1. comments,
2. simple and complex variables (e.g. struct elements and volatile global variables),
3. security policies,
4. predicates on the initial state, and

5. loop invariants.

Each test was conducted to assess the viability of each approach of preserving annotations. If the approach cannot preserve all the required annotations described in the aforementioned list, then it is not viable for a wpif analysis and another technique must be explored.

The justification for each of the test files are as follows:

comment.c

This test case is primarily a stepping stone to testing more complex scenarios. Here we have a generic comment "critical comment" and we are looking to preserve it through to the assembly. As well as preserving the comment itself, the location of the comment within the source code is to be preserved.

variable.c

The test file *variable.c* builds off *comment.c*, however, we are additionally looking to preserve annotations about local variables within the program. Here multiple variable types are tested:

- int,
- char,
- unsigned int,
- short,
- long,
- float, and
- double.

With each of these variables their type data is included as an annotation. This test is particularly interesting as with higher levels of optimisation we can observe how the annotations behave when a variable is optimised out.

volatile.c

This test program looks at how the technique handles volatile variables. A variable declared as volatile tells the program its value could change unexpectedly. This is especially important when dealing with concurrent programs. If the technique cannot handle

volatile variables it is unable to be used for a wpif analysis.

loop.c

This test program tests how the annotator handles loops and loop invariants. It contains security policies, predicates on the initial state and loop invariants.

rooster.c

The test program, *rooster.c* delves into a more complex program, combining several features of the previous tests. It contains annotations within functions and global variables.

password.c

This program tests how annotations are preserved within structs, a user-defined data type. Additionally, *password.c* is a more complex program with multiple functions.

deadStoreElimination.c

Testing dead store elimination is a bit more complex, as it requires comparing the compiled output before and after compiler optimisations are turned on. Here, the test program simulates the program described in section 2.4.

pread.c

The program *pread.c* is a culmination of all the previous test cases, and is similar to *loop.c*, however, the global variables within it are volatile. It requires all the necessary components for a wpif analysis.

3.2 Quality Analysis

Although a method of preserving c annotations may be able to successfully pass all the test cases, it is important to avoid modifying the assembly instructions. The reason for performing a static analysis on the compiled output is due to the optimisations performed by the compiler. As such, it is important to ensure that preserved annotations do not remove or undo any optimisations that may have been performed by the compiler.

The methodology for testing quality in this manner is to compare the compiled assembly output for a program with annotations on to the compiled assembly output for the same program without annotations. If unnecessary assembly instructions have

been added, it is indicative that the annotations has modified the program in unintended ways.

3.3 Efficiency and Optimisation

In the case that the annotations have introduced additional statements into the compiled assembly output, understanding the extent of these changes is important. Here, a efficiency analysis can be conducted on the assembly. Using big O notation, an upper bound can be placed on the program. Doing so allows for a comparison of the efficiency of the annotated and non-annotated assembly.

Let $A(n)$ be the function describing the annotated assembly, and $B(n)$ be the function describing the non-annotated assembly. Then,

$$A(n) \in \Theta(g(n))$$

$$B(n) \in \Theta(h(n))$$

If the non-annotated assembly has a lower bound than the annotated assembly, such that

$$h(n) \in O(g(n)), \text{ and}$$

$$g(n) \notin O(h(n))$$

then the annotations have modified the program in a way that reduces runtime efficiency. It is important to detect when this has happened, as it indicates the annotations have reversed the intended compiler optimisations.

In the case where the annotation process has resulted in additional assembly instructions inserted into the compiled output, however, they do not reduce runtime efficiency in terms of big O notation, a empirical analysis of the runtime duration of a program can be conducted to assess the disadvantage of the annotated program.

3.4 Tool Development

In cases where it is appropriate, a tool may be developed to assist in the annotating process. This tool may either:

- assist in the annotating process,

- verify the correctness of the annotations, or
- perform additional analysis on the compiled output.

If the approach of modifying the LLVM compiler is pursued, developing such a tool to assist the annotating process will be necessary.

4 Execution

Experimentation began with the CompCert compiler and the provided assembly annotation tools, outlined in section 4.1. It was found that the CompCert compiler could not handle all cases necessary for the wpif analysis, specifically volatile variables. As a result, the testing moved on to other techniques. Following this, the GNU C extension for inline assembly was explored as a possibility to preserve annotations in C in section 4.2. This technique prevailed and was found to be excellent in handling assembly annotations by injecting comments in to the compiled assembly output. This technique was enhanced by developing a python program to inject inline assembly into the source C files to allow for enhanced analysis and furthermore avoids restricting the program to GNU extension supporting compilers. As a result of the success, modifying the compiler was not explored due to success documented in other research such as the work conducted by Vu et al. [30]. This allowed for further development and improvement of the inline assembly method.

4.1 CompCert AIS Annotations

CompCert is unfortunately not a free tool, however, for research purposes it can be used freely. The specifications of the CompCert install can be seen in Table 1.

Testing was initially conducted using the *comment.c* test file. The goal is to propagate the comment down to assembly where it can be used and interpreted. To do so, the comment in the source code needs to be replaced with a call to generate an annotation in the compiled assembly. Fortunately, with the CompCert compiler, this functionality is

OS Name	Ubuntu 20.04.2 LTS
OS Type	64-bit
Processor	Intel® Core™ i7-6700K CPU @ 4.00GHz × 8
Instruction Set	x86-64
CompCert Version	The CompCert C verified compiler, version 3.7

Table 1: CompCert install specifications

builtin. This assembly annotation is created through the use of the `__builtin_annot` function described in 2.6. The following builtin annotation was placed in line 2, within the main function in *comment.c*.

```
2  __builtin_ais_annot("%here Critical
    Comment");
```

Listing 1: comment.c

Within this annotation, `%here` is used to represent the location within the program. If the location is not important, `%here` can be omitted. The comment, "Critical Comment", has been included to represent some kind of critical comment that is required to conduct a static analysis on the output. To compile the source to assembler only the following command was used:

```
$ ccomp comment.c -O0 -S
```

Here -O0 is used to specify to perform no optimisations during compilation. The full compiled output can be seen in Appendix C.16. Below is a snippet of the compiled assembly.

```
16  .cfi_endproc
17  .type main, @function
18  .size main, . - main
19  .section
    "__compcert_ais_annotations","",@note
20  .ascii "# file:comment.c line:2
    function:main\n"
21  .byte 7,8
22  .quad .L100
23  .ascii " Critical Comment\n"
```

Listing 2: comment-O0.s

The annotation is stored within assembler directives. Assembler directives are not a part of the pro-

cessor instruction set, however, are a part of the assembler syntax. Assembler directives all start a period (.). On line 19 a new section has been created, named "`__compcert_ais_annotations`". Following the declaration of the section is an ascii string, locating the source of the annotation within the source program *comment.c*. Line 23 provides the comment we aimed to preserve with our annotation. Thus, CompCert has shown an initial success in preserving annotations in the form of comments.

Additionally, one major benefit of compCert annotations is that they do not modify the source program, as they are inserted at the end of the program as an assembler directive metadata.

When experimenting with annotated variables, the first issues began to arise. The test file *variable.c* contains several variables with their types to preserve to assembly. The annotations behaved as expected for the types:

- int,
- char,
- short,
- long, and
- any signed or unsigned variations of the above mentioned types.

However, the CompCert annotations does not support floating point types. Upon compiling *variable.c* the following errors were generated.

```
variable.c:13: error: floating point types
    for parameter '%e1' are not supported
    in ais annotations
variable.c:15: error: floating point types
    for parameter '%e1' are not supported
    in ais annotations
2 errors detected.
```

This result shows that it is impossible to use the CompCert embedded program annotations for floating point types, vastly restricting its potential use as a technique for a wpif analysis.

It was discovered soon after that the CompCert annotations are unable to handle volatile variables, generating the follow error upon compiling *volatile.c*.

```
volatile.c:4: error: access to volatile
    variable 'x' for parameter '%e1' is not
    supported in ais annotations
1 error detected.
```

Unfortunately, this result shows that the CompCert AIS annotations approach is not suitable for wpif analysis. The wpif analysis requires use of volatile variables. This is because the primary purpose of the wpif technique is to verify security policy across concurrent programs. Shared variables within concurrent programs can change at any time, and as such it is imperative that shared variables are marked as volatile. As the CompCert AIS annotations cannot handle volatile variables, annotations required for wpif analysis cannot be generated.

Aside from the aforementioned issues, the CompCert AIS annotations performed excellently in generating annotations. The location of global variables in memory are easily identified, as shown in *rooster.c*. The CompCert AIS annotations must be placed within a method and called as if it was its own function. This creates some confusion when dealing with global variables. However, placing annotations on global variables at the start of main is a perfectly valid method of preserving these annotations. As the location of the annotation within the program is no longer important, the `%here` format specifier can be omitted.

```
84 .cfi_endproc
85 .type main, @function
86 .size main, . - main
87 .section
    "__compcert_ais_annotations","",@note
88 .ascii "# file:rooster.c line:6
    function:fun\n"
89 .byte 7,8
90 .quad .L100
91 .ascii " CRITICAL COMMENT\n"
92 .ascii "# file:rooster.c line:26
    function:main\n"
93 .byte 7,8
94 .quad .L107
95 .ascii " L(mem("
96 .byte 7,8
97 .quad goose
98 .ascii ", 4)) = medium\n"
99 .ascii "# file:rooster.c line:27
    function:main\n"
100 .byte 7,8
101 .quad .L108
```

```
102 .ascii " EXCEPTIONAL\n"
```

Listing 3: rooster-O0.s

From *rooster.c*, the comment "CRITICAL COMMENT" has been annotated from lines 88 to 91, and the comment "EXCEPTIONAL" has been annotated from lines 99 to 102. Most notably, the global variable `goose` has been annotated from lines 92 to 98. Reconstructed, the string `"L(mem(goose, 4)) = medium"` has been preserved. Thus, the CompCert annotations can successfully preserve annotations on global variables.

Another interesting problem faced when working with CompCert AIS annotations is found when working with structs. If the programmer wants to annotate a member of a struct for all structs of that type, each instance of that type of struct must be annotated when using CompCert AIS annotations. This is because CompCert treats `__builtin_ais_annot()` as a call to an external function. As such, an annotation cannot be created from outside a method, similar to when dealing with global variables. An example of this process can be seen in *password.c*. Within the program, each instantiation of the struct `user_t` requires another annotation.

```
17 user_t* user_admin =  
    malloc(sizeof(user_t));  
18 strcpy(user_admin->name, "admin");  
19 strcpy(user_admin->password,  
    "4dmin__4eva");  
20 __builtin_ais_annot("%here L(%e1) =  
    high", user_admin->password);  
21 user_admin->balance = 1000000;  
22  
23 user_t* user_alice =  
    malloc(sizeof(user_t));  
24 strcpy(user_alice->name, "alice");  
25 strcpy(user_alice->password,  
    "!alice12!_veujs@hah");  
26 __builtin_ais_annot("%here L(%e1) =  
    high", user_alice->password);  
27 user_alice->balance = 783;  
28  
29 user_t* user_abdul =  
    malloc(sizeof(user_t));  
30 strcpy(user_abdul->name, "abdul");  
31 strcpy(user_abdul->password,  
    "passw0rd123");  
32 __builtin_ais_annot("%here L(%e1) =  
    high", user_abdul->password);
```

```
33 user_abdul->balance = 2;
```

Listing 4: password.c

4.1.1 Quality Analysis

- TODO: How good is the compcert yo

4.2 Inline Assembly

TODO: Inline assembly techniques

4.3 CompCert Builtin Annotations

4.4 LLVM Compiler Modification

the final technique of modifying the LLVM compiler was not experimented on. This was primarily due to two reasons. To begin with, the primary objective of this thesis is to explore techniques that do not modify the compiler, and instead work alongside the functionality of the compiler to preserve annotations. It is well known and documented that modifying the compiler to preserve annotations is possible and successful, as in the case of Vu et al. [30] Additionally, earlier success through the technique of using inline assembly allowed for more time to be allocated to exploring and improving this technique, as seen in 4.2. Therefore, evaluating compiler modification for static analysis purposes was not performed in this research.

References

- [1] Pieter Agten et al. “Recent developments in low-level software security”. In: *IFIP International Workshop on Information Security Theory and Practice*. Springer. 2012, pp. 1–16.
- [2] Musard Balliu. “Logics for information flow security: from specification to verification”. PhD thesis. KTH Royal Institute of Technology, 2014.
- [3] Nick Benton. “Simple relational correctness proofs for static analyses and program transformations”. In: *ACM SIGPLAN Notices* 39.1 (2004), pp. 14–25.
- [4] *CompCert - The CompCert C compiler*. Accessed: 2020-09-01. 2020. URL: <http://compcert.inria.fr/compcert-C.html>.
- [5] *Compiler Optimization Removal or Modification of Security-critical Code*. Accessed: 2020-09-01. 2008. URL: <https://cwe.mitre.org/data/definitions/733.html>.
- [6] *Compiler Removal of Code to Clear Buffers*. Accessed: 2020-09-01. 2006. URL: <https://cwe.mitre.org/data/definitions/14.html>.
- [7] Vijay D’Silva, Mathias Payer, and Dawn Song. “The correctness-security gap in compiler optimization”. In: *2015 IEEE Security and Privacy Workshops*. IEEE. 2015, pp. 73–87.
- [8] Dorothy E Denning. “A lattice model of secure information flow”. In: *Communications of the ACM* 19.5 (1976), pp. 236–243.
- [9] Dorothy E Denning and Peter J Denning. “Certification of programs for secure information flow”. In: *Communications of the ACM* 20.7 (1977), pp. 504–513.
- [10] Quang Do, Ben Martini, and Kim-Kwang Raymond Choo. “The role of the adversary model in applied security research”. In: *Computers & Security* 81 (2019), pp. 156–181.
- [11] K Eder, K Georgiou, and N Grech. *Common Assertion Language. ENTRA Project: Whole-Systems Energy Transparency (FET project 318337). Deliverable 2.1*. 2013.
- [12] Gidon Ernst and Toby Murray. “SecCSL: Security concurrent separation logic”. In: *International Conference on Computer Aided Verification*. Springer. 2019, pp. 208–230.
- [13] *File:Simplified Heartbleed explanation.svg - Wikimedia Commons*. Accessed: 2020-09-02. 2014. URL: https://commons.wikimedia.org/wiki/File:Simplified_Heartbleed_explanation.svg#mediaviewer/File:Simplified_Heartbleed_explanation.svg.
- [14] *GCC Developer Options*. Accessed: 2020-09-02. URL: <https://gcc.gnu.org/onlinedocs/gcc/Developer-Options.html>.
- [15] Barbara Guttman and Edward A Roback. *An introduction to computer security: the NIST handbook*. Diane Publishing, 1995.
- [16] *Heartbleed Bug*. Accessed: 2020-09-02. 2020. URL: <https://heartbleed.com/>.
- [17] Xavier Leroy. “Formal certification of a compiler back-end or: programming a compiler with a proof assistant”. In: *Conference record of the 33rd ACM SIGPLAN-SIGACT symposium on Principles of programming languages*. 2006, pp. 42–54.
- [18] Xavier Leroy et al. “CompCert-a formally verified optimizing compiler”. In: 2016.
- [19] Heiko Mantel, Matthias Perner, and Jens Sauer. “Noninterference under weak memory models”. In: *2014 IEEE 27th Computer Security Foundations Symposium*. IEEE. 2014, pp. 80–94.
- [20] Heiko Mantel, David Sands, and Henning Sudbrock. “Assumptions and guarantees for compositional noninterference”. In: *2011 IEEE 24th Computer Security Foundations Symposium*. IEEE. 2011, pp. 218–232.

- [21] Toby Murray, Robert Sison, and Kai Engelhardt. “COVERN: A logic for compositional verification of information flow control”. In: *2018 IEEE European Symposium on Security and Privacy (EuroS&P)*. IEEE. 2018, pp. 16–30.
- [22] *Options That Control Optimization*. Accessed: 2020-09-01. URL: <https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html>.
- [23] Sundeeep Prakash, Yann-Hang Lee, and Theodore Johnson. “Non-blocking algorithms for concurrent data structures”. MA thesis. Citeseer, 1991.
- [24] Andrei Sabelfeld and Andrew C Myers. “Language-based information-flow security”. In: *IEEE Journal on selected areas in communications* 21.1 (2003), pp. 5–19.
- [25] Bernhard Schommer et al. “Embedded program annotations for WCET analysis”. In: *18th International Workshop on Worst-Case Execution Time Analysis (WCET 2018)*. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik. 2018.
- [26] Laurent Simon, David Chisnall, and Ross Anderson. “What you get is what you C: Controlling side effects in mainstream C compilers”. In: *2018 IEEE European Symposium on Security and Privacy (EuroS&P)*. IEEE. 2018, pp. 1–15.
- [27] Graeme Smith, Nicholas Coughlin, and Toby Murray. “Value-Dependent Information-Flow Security on Weak Memory Models”. In: *International Symposium on Formal Methods*. Springer. 2019, pp. 539–555.
- [28] William Stallings et al. *Computer security: principles and practice*. Pearson Education Upper Saddle River, NJ, USA, 2012.
- [29] Jeffrey A Vaughan and Todd Millstein. “Secure information flow for concurrent programs under total store order”. In: *2012 IEEE 25th Computer Security Foundations Symposium*. IEEE. 2012, pp. 19–29.
- [30] Son Tuan Vu et al. “Secure delivery of program properties through optimizing compilation”. In: *Proceedings of the 29th International Conference on Compiler Construction*. 2020, pp. 14–26.
- [31] Kirsten Winter, Graeme Smith, and Nicholas Coughlin. “Information flow security in the presence of fine-grained concurrency”. Unpublished. Aug. 2020.

Appendices

A Test C Programs

A.1 comment.c

```
1 int main() {  
2     // Critical Comment  
3     return 0;  
4 }
```

A.2 variable.c

```
1 int main(int argc, char* argv[]) {  
2     // a = int  
3     // b = char  
4     // c = unsigned int  
5     // d = short  
6     // e = long  
7     // x = float  
8     // y = double  
9     int a = -10;  
10    char b = 'b';  
11    unsigned int c = -b;  
12    short d = 0x1;  
13    long e = 4294967296;  
14    float x = 3.141592653589793;  
15    double y = x / 2.3784;  
16    return (int)(e / 32) + (int)a + (int)c + (int)d + (int)x + (int)y + argc;  
17 }
```

A.3 volatile.c

```
1 volatile int x;  
2  
3 int main() {  
4     // L(x) = High  
5     return x + 1;  
6 }
```

A.4 loop.c

```
1 int z;  
2 int x;  
3  
4 // security policies  
5 // {L(z)=true}  
6 // {L(x)=z % 2 == 0}  
7  
8 // predicates on initial state  
9 // {_P_0: r1 % 2 == 0}  
10 // {_Gamma_0: r1 -> LOW, r2 -> LOW}  
11  
12 int main() {
```

```

13  int r1 = 0;
14  // {L(r2)=False}
15  int r2 = 0;
16
17  while(1) {
18  do {
19      // {_invariant: r1 % 2 == 0 /\ r1 <= z}
20      // {_Gamma: r1 -> LOW, r2 -> (r1 == z), z -> LOW}
21      do {
22          // {_invariant: r1 <= z}
23          // {_Gamma: r1 -> LOW}
24          r1 = z;
25      } while (r1 %2 != 0);
26      r2 = x;
27      } while (z != r1);
28  }
29  return r2;
30 }

```

A.5 rooster.c

```

1  int rooster;
2  int drake;
3  // MEDIUM
4  int goose;
5
6  int fun(int a, int b, int c) {
7      // CRITICAL COMMENT
8      static int count = 0;
9      int sum = a + b + c;
10     if (sum < 0) {
11         return sum;
12     }
13     if (a < b && b < c) {
14         while (a != b) {
15             a++;
16             count++;
17             while (b != c) {
18                 c--;
19                 count++;
20             }
21         }
22     }
23     return count;
24 }
25
26 int main(void) {
27     // EXCEPTIONAL
28     rooster = 1;
29     drake = 5;
30     goose = 10;
31     int result;
32     result = fun(rooster, drake, goose);
33     return 0;
34 }

```

A.6 password.c

```

1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <string.h>
4
5 #define BUFF_LEN 256
6
7 typedef struct user_t user_t;
8
9 struct user_t {
10     user_t* next;
11     char name[BUFF_LEN];
12     // L(password) = High
13     char password[BUFF_LEN];
14     size_t balance;
15 };
16
17 user_t* setup_users() {
18     user_t* user_admin = malloc(sizeof(user_t));
19     strcpy(user_admin->name, "admin");
20     strcpy(user_admin->password, "4dmin__4eva");
21     user_admin->balance = 1000000;
22
23     user_t* user_alice = malloc(sizeof(user_t));
24     strcpy(user_alice->name, "alice");
25     strcpy(user_alice->password, "!alice12!_veujs@h4k");
26     user_alice->balance = 783;
27
28     user_t* user_abdul = malloc(sizeof(user_t));
29     strcpy(user_abdul->name, "abdul");
30     strcpy(user_abdul->password, "passw0rd123");
31     user_abdul->balance = 2;
32
33     user_admin->next = user_alice;
34     user_alice->next = user_abdul;
35     user_abdul->next = NULL;
36
37     return user_admin;
38 }
39
40 void print_users(user_t* users) {
41     printf("--- USERS ---\n");
42     size_t count = 0;
43     while (users != NULL) {
44         printf(" %02ld. %s\n", ++count, users->name);
45         users = users->next;
46     }
47     printf("\n");
48 }
49
50 user_t* getUser(user_t* user_list, char* name) {
51     while (user_list != NULL) {
52         if (strcmp(user_list->name, name) == 0) {
53             return user_list;
54         }
55         user_list = user_list->next;
56     }
57     return NULL;

```



```

58 }
59
60 int main() {
61     user_t* users = setup_users();
62
63     printf("Welcome to BigBank Australia!\n");
64
65     char username[BUFF_LEN];
66     printf("Username: ");
67     scanf("%255s", username);
68
69     user_t* user = getUser(users, username);
70     if (user == NULL) {
71         printf("User < %s > does not exist.\n", username);
72         return 0;
73     }
74
75     char password[BUFF_LEN];
76     printf("Password: ");
77     scanf("%255s", password);
78     if (strcmp(user->password, password) != 0) {
79         printf("ERROR: incorrect password\n");
80         return 0;
81     }
82
83     printf("Logged in as < %s >!\n", user->name);
84     printf("\n");
85     printf("Welcome, %s!\n", user->name);
86     printf("Your balance: $%ld\n", user->balance);
87 }

```

A.7 deadStoreElimination.c

```

1 int deadStore(int i, int n) {
2     int key = 0xabcd;
3     // L(key) = high
4
5     // do some work
6     int result = 0;
7     while (i > n) {
8         result += key;
9         i--;
10    }
11
12    // clear out our secret key
13    key = 0;
14    return i + n;
15 }
16
17 int main(int argc, char *argv[]) {
18     deadStore(argc, 2);
19 }

```

A.8 pread.c

```

1 volatile int z;
2 volatile int x;

```

```

3
4 // security policies
5 // {L(z)=true}
6 // {L(x)=z % 2 == 0}
7
8 // predicates on initial state
9 // {_P_0: r1 % 2 == 0}
10 // {_Gamma_0: r1 -> LOW, r2 -> LOW}
11
12 int main() {
13     int r1 = 0;
14     // {L(r2)=False}
15     int r2 = 0;
16
17     while(1) {
18     do {
19         // {_invariant: r1 % 2 == 0 /\ r1 <= z}
20         // {_Gamma: r1 -> LOW, r2 -> (r1 == z), z -> LOW}
21         do {
22             // {_invariant: r1 <= z}
23             // {_Gamma: r1 -> LOW}
24             r1 = z;
25         } while (r1 % 2 != 0);
26         r2 = x;
27     } while (z != r1);
28     }
29     return r2;
30 }

```

B CompCert Annotated C Programs

B.1 comment.c

```

1 int main() {
2     __builtin_ais_annot("%here Critical Comment");
3     return 0;
4 }

```

B.2 variable.c

```

1 int main(int argc, char* argv[]) {
2     int a = -10;
3     __builtin_ais_annot("%here %e1 = int", a);
4     char b = 'b';
5     __builtin_ais_annot("%here %e1 = char", b);
6     unsigned int c = -b;
7     __builtin_ais_annot("%here %e1 = unsigned int", c);
8     short d = 0x1;
9     __builtin_ais_annot("%here %e1 = short", d);
10    long e = 4294967296;
11    __builtin_ais_annot("%here %e1 = long", e);
12    float x = 3.141592653589793;
13    __builtin_ais_annot("%here %e1 = float", x);
14    double y = x / 2.3784;
15    __builtin_ais_annot("%here %e1 = double", y);
16    return (int)(e / 32) + (int)a + (int)c + (int)d + (int)x + (int)y + argc;

```

```
17 }
```

B.3 volatile.c

```
1 volatile int x;
2
3 int main() {
4     __builtin_ais_annot("%here L(%e1)= false", x);
5     return x + 1;
6 }
```

B.4 loop.c

```
1
2 int z;
3 int x;
4
5 int main() {
6     // Security Policies
7     __builtin_ais_annot("%here L(%e1) = true", z);
8     __builtin_ais_annot("%here L(%e1)= %e2 %% 2 == 0", x, z);
9     int r1 = 0;
10    int r2 = 0;
11    __builtin_ais_annot("%here L(%e1)= false", r2);
12
13    // Predicates on initial state
14    __builtin_ais_annot("%here _P_0: %e1 %% 2 == 0", r1);
15    __builtin_ais_annot("%here _Gamma_0: %e1 -> LOW, %e2 -> LOW", r1, r2);
16
17    while(1) {
18        do {
19            __builtin_ais_annot("%here _invariant: %e1 %% 2 == 0 & %e1 <= %e2", r1, z);
20            __builtin_ais_annot("%here _Gamma: %e1 -> LOW, %e2 -> (%e1 == %e3), %e3 -> LOW",
21            r1, r2, z);
22            do {
23                __builtin_ais_annot("%here _invariant: %e1 <= %e2", r1, z);
24                __builtin_ais_annot("%here _Gamma: %e1 -> LOW", r1);
25                r1 = z;
26            } while (r1 %2 != 0);
27            r2 = x;
28            } while (z != r1);
29        }
30    return r2;
31 }
```

B.5 rooster.c

```
1 int rooster;
2 int drake;
3 int goose;
4
5 int fun(int a, int b, int c) {
6     __builtin_ais_annot("%here CRITICAL COMMENT");
7     static int count = 0;
8     int sum = a + b + c;
9     if (sum < 0) {
10         return sum;
11     }
```

```

11     }
12     if (a < b && b < c) {
13         while (a != b) {
14             a++;
15             count++;
16             while (b != c) {
17                 c--;
18                 count++;
19             }
20         }
21     }
22     return count;
23 }
24
25 int main(void) {
26     __builtin_ais_annot("%here L(%e1) = medium", goose);
27     __builtin_ais_annot("%here EXCEPTIONAL");
28     rooster = 1;
29     drake = 5;
30     goose = 10;
31     int result;
32     result = fun(rooster, drake, goose);
33     return 0;
34 }

```

B.6 password.c

```

1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <string.h>
4
5 #define BUFF_LEN 256
6
7 typedef struct user_t user_t;
8
9 struct user_t {
10     user_t* next;
11     char name[BUFF_LEN];
12     char password[BUFF_LEN];           // { L(password) = High }
13     size_t balance;
14 };
15
16 user_t* setup_users() {
17     user_t* user_admin = malloc(sizeof(user_t));
18     strcpy(user_admin->name, "admin");
19     strcpy(user_admin->password, "4dmin_4eva");
20     __builtin_ais_annot("%here L(%e1) = high", user_admin->password);
21     user_admin->balance = 1000000;
22
23     user_t* user_alice = malloc(sizeof(user_t));
24     strcpy(user_alice->name, "alice");
25     strcpy(user_alice->password, "!alice12!_veujs@h@k");
26     __builtin_ais_annot("%here L(%e1) = high", user_alice->password);
27     user_alice->balance = 783;
28
29     user_t* user_abdul = malloc(sizeof(user_t));
30     strcpy(user_abdul->name, "abdul");

```

```

31 strcpy(user_abdul->password, "passw0rd123");
32 __builtin_ais_annot("%here L(%e1) = high", user_abdul->password);
33 user_abdul->balance = 2;
34
35 user_admin->next = user_alice;
36 user_alice->next = user_abdul;
37 user_abdul->next = NULL;
38
39 return user_admin;
40 }
41
42 void print_users(user_t* users) {
43     printf("--- USERS ---\n");
44     size_t count = 0;
45     while (users != NULL) {
46         printf(" %02ld. %s\n", ++count, users->name);
47         users = users->next;
48     }
49     printf("\n");
50 }
51
52 user_t* getUser(user_t* user_list, char* name) {
53     while (user_list != NULL) {
54         if (strcmp(user_list->name, name) == 0) {
55             return user_list;
56         }
57         user_list = user_list->next;
58     }
59     return NULL;
60 }
61
62 int main() {
63     user_t* users = setup_users();
64
65     printf("Welcome to BigBank Australia!\n");
66
67     char username[BUFF_LEN];
68     printf("Username: ");
69     scanf("%255s", username);
70
71     user_t* user = getUser(users, username);
72     if (user == NULL) {
73         printf("User < %s > does not exist.\n", username);
74         return 0;
75     }
76
77     char password[BUFF_LEN];
78     printf("Password: ");
79     scanf("%255s", password);
80     if (strcmp(user->password, password) != 0) {
81         printf("ERROR: incorrect password\n");
82         return 0;
83     }
84
85     printf("Logged in as < %s >!\n", user->name);
86     printf("\n");
87     printf("Welcome, %s!\n", user->name);

```

```

88     printf("Your balance: %ld\n", user->balance);
89 }

```

B.7 deadStoreElimination.c

```

1  int deadStore(int i, int n) {
2      int key = 0xabcd;
3      __builtin_ais_annot("%here L(%e1) = high", key);
4
5      // do some work
6      int result = 0;
7      while (i > n) {
8          result += key;
9          i--;
10     }
11
12     // clear out our secret key
13     key = 0;
14     return i + n;
15 }
16
17 int main(int argc, char *argv[]) {
18     deadStore(argc, 2);
19 }

```

B.8 pread.c

```

1  volatile int z;
2  volatile int x;
3
4  int main() {
5      // Security Policies
6      __builtin_ais_annot("%here L(%e1) = true", z);
7      __builtin_ais_annot("%here L(%e1)= %e2 %% 2 == 0", x, z);
8
9      int r1 = 0;
10     int r2 = 0; // {L(r2)=False}
11     __builtin_ais_annot("%here L(%e1)= false", r2);
12
13     // Predicates on initial state
14     __builtin_ais_annot("%here _P_0: %e1 %% 2 == 0", r1);
15     __builtin_ais_annot("%here _Gamma_0: %e1 -> LOW, %e2 -> LOW", r1, r2);
16
17
18     while(1) {
19         do {
20             __builtin_ais_annot("%here _invariant: %e1 %% 2 == 0 & %e1 <= %e2", r1, z);
21             __builtin_ais_annot("%here _Gamma: %e1 -> LOW, %e2 -> (%e1 == %e3), %e3 ->
22             LOW", r1, r2, z);
23             do {
24                 __builtin_ais_annot("%here _invariant: %e1 <= %e2", r1, z);
25                 __builtin_ais_annot("%here _Gamma: %e1 -> LOW", r1);
26                 r1 = z;
27             } while (r1 % 2 != 0);
28             r2 = x;
29         } while (z != r1);
30     }
31 }

```

```

30     return r2;
31 }

```

C CompCert Annotated Assembly Output

C.1 comment-O0.s

```

1 # File generated by CompCert 3.7
2 # Command line: comment.c -O0 -S
3 .text
4 .align 16
5 .globl main
6 main:
7 .cfi_startproc
8 subq $8, %rsp
9 .cfi_adjust_cfa_offset 8
10 leaq 16(%rsp), %rax
11 movq %rax, 0(%rsp)
12 .L100:
13 xorl %eax, %eax
14 addq $8, %rsp
15 ret
16 .cfi_endproc
17 .type main, @function
18 .size main, . - main
19 .section "__compcert_ais_annotations","",@note
20 .ascii "# file:comment.c line:2 function:main\n"
21 .byte 7,8
22 .quad .L100
23 .ascii " Critical Comment\n"

```

C.2 comment-O3.s

```

1 # File generated by CompCert 3.7
2 # Command line: comment.c -O3 -S
3 .text
4 .align 16
5 .globl main
6 main:
7 .cfi_startproc
8 subq $8, %rsp
9 .cfi_adjust_cfa_offset 8
10 leaq 16(%rsp), %rax
11 movq %rax, 0(%rsp)
12 .L100:
13 xorl %eax, %eax
14 addq $8, %rsp
15 ret
16 .cfi_endproc
17 .type main, @function
18 .size main, . - main
19 .section "__compcert_ais_annotations","",@note
20 .ascii "# file:comment.c line:2 function:main\n"
21 .byte 7,8
22 .quad .L100
23 .ascii " Critical Comment\n"

```

C.3 variable-00.s

```
1 # File generated by CompCert 3.7
2 # Command line: variable.c -S -O0
3 .text
4 .align 16
5 .globl main
6 main:
7 .cfi_startproc
8 subq $8, %rsp
9 .cfi_adjust_cfa_offset 8
10 leaq 16(%rsp), %rax
11 movq %rax, 0(%rsp)
12 movl $-10, %esi
13 .L100:
14 movl $98, %ecx
15 .L101:
16 negl %ecx
17 .L102:
18 movl $1, %r10d
19 .L103:
20 movabsq $4294967296, %rax
21 .L104:
22 movsd .L105(%rip), %xmm1 # 3.14159265358979312
23 cvtsd2ss %xmm1, %xmm3
24 cvtss2sd %xmm3, %xmm0
25 movsd .L106(%rip), %xmm2 # 2.378400000000000007
26 divsd %xmm2, %xmm0
27 cqto
28 shrq $59, %rdx
29 leaq 0(%rax,%rdx,1), %rax
30 sarq $5, %rax
31 leal 0(%eax,%esi,1), %r9d
32 leal 0(%r9d,%ecx,1), %r8d
33 leal 0(%r8d,%r10d,1), %r10d
34 cvttss2si %xmm3, %edx
35 leal 0(%r10d,%edx,1), %r11d
36 cvttsd2si %xmm0, %r8d
37 leal 0(%r11d,%r8d,1), %ecx
38 leal 0(%ecx,%edi,1), %eax
39 addq $8, %rsp
40 ret
41 .cfi_endproc
42 .type main, @function
43 .size main, . - main
44 .section .rodata.cst8,"aM",@progbits,8
45 .align 8
46 .L105: .quad 0x400921fb54442d18
47 .L106: .quad 0x400306f694467382
48 .section "__compcert_ais_annotations","",@note
49 .ascii "# file:variable.c line:3 function:main\n"
50 .byte 7,8
51 .quad .L100
52 .ascii " reg(\"rsi\") = int\n"
53 .ascii "# file:variable.c line:5 function:main\n"
54 .byte 7,8
55 .quad .L101
```



```

56 .ascii " reg(\"rcx\") = char\n"
57 .ascii "# file:variable.c line:7 function:main\n"
58 .byte 7,8
59 .quad .L102
60 .ascii " reg(\"rcx\") = unsigned int\n"
61 .ascii "# file:variable.c line:9 function:main\n"
62 .byte 7,8
63 .quad .L103
64 .ascii " reg(\"r10\") = short\n"
65 .ascii "# file:variable.c line:11 function:main\n"
66 .byte 7,8
67 .quad .L104
68 .ascii " reg(\"rax\") = long\n"

```

C.4 variable-O3.s

```

1 # File generated by CompCert 3.7
2 # Command line: variable.c -S -O3
3 .text
4 .align 16
5 .globl main
6 main:
7 .cfi_startproc
8 subq $8, %rsp
9 .cfi_adjust_cfa_offset 8
10 leaq 16(%rsp), %rax
11 movq %rax, 0(%rsp)
12 .L100:
13 .L101:
14 .L102:
15 .L103:
16 .L104:
17 leal 134217625(%edi), %eax
18 addq $8, %rsp
19 ret
20 .cfi_endproc
21 .type main, @function
22 .size main, . - main
23 .section "__compcert_ais_annotations","",@note
24 .ascii "# file:variable.c line:3 function:main\n"
25 .byte 7,8
26 .quad .L100
27 .ascii " -10 = int\n"
28 .ascii "# file:variable.c line:5 function:main\n"
29 .byte 7,8
30 .quad .L101
31 .ascii " 98 = char\n"
32 .ascii "# file:variable.c line:7 function:main\n"
33 .byte 7,8
34 .quad .L102
35 .ascii " -98 = unsigned int\n"
36 .ascii "# file:variable.c line:9 function:main\n"
37 .byte 7,8
38 .quad .L103
39 .ascii " 1 = short\n"
40 .ascii "# file:variable.c line:11 function:main\n"
41 .byte 7,8

```

```

42 .quad .L104
43 .ascii " 4294967296 = long\n"

```

C.5 volatile-O0.s

```

1 volatile.c:4: error: access to volatile variable 'x' for parameter '%e1' is not supported
    in ais annotations
2 1 error detected.

```

C.6 volatile-O3.s

```

1 volatile.c:4: error: access to volatile variable 'x' for parameter '%e1' is not supported
    in ais annotations
2 1 error detected.

```

C.7 loop-O0.s

```

1 # File generated by CompCert 3.7
2 # Command line: loop.c -O0 -S
3 .comm z, 4, 4
4 .comm x, 4, 4
5 .text
6 .align 16
7 .globl main
8 main:
9 .cfi_startproc
10 subq $8, %rsp
11 .cfi_adjust_cfa_offset 8
12 leaq 16(%rsp), %rax
13 movq %rax, 0(%rsp)
14 .L100:
15 .L101:
16 xorl %edx, %edx
17 xorl %edi, %edi
18 .L102:
19 .L103:
20 .L104:
21 nop
22 .L105:
23 .L106:
24 .L107:
25 nop
26 .L108:
27 .L109:
28 .L110:
29 movl z(%rip), %edx
30 movq %rdx, %rax
31 testl %eax, %eax
32 leal 1(%eax), %ecx
33 cmovl %rcx, %rax
34 sarl $1, %eax
35 leal 0(,%eax,2), %edi
36 movq %rdx, %rcx
37 subl %edi, %ecx
38 testl %ecx, %ecx
39 jne .L108
40 movl x(%rip), %edi

```

```

41 movl z(%rip), %esi
42 jmp .L105
43 .cfi_endproc
44 .type main, @function
45 .size main, . - main
46 .section "__compcert_ais_annotations","",@note
47 .ascii "# file:loop.c line:7 function:main\n"
48 .byte 7,8
49 .quad .L100
50 .ascii " L(mem("
51 .byte 7,8
52 .quad z
53 .ascii ", 4)) = true\n"
54 .ascii "# file:loop.c line:8 function:main\n"
55 .byte 7,8
56 .quad .L101
57 .ascii " L(mem("
58 .byte 7,8
59 .quad x
60 .ascii ", 4))= mem("
61 .byte 7,8
62 .quad z
63 .ascii ", 4) % 2 == 0\n"
64 .ascii "# file:loop.c line:11 function:main\n"
65 .byte 7,8
66 .quad .L102
67 .ascii " L(reg(\"rdi\"))= false\n"
68 .ascii "# file:loop.c line:14 function:main\n"
69 .byte 7,8
70 .quad .L103
71 .ascii " _P_0: reg(\"rdx\") % 2 == 0\n"
72 .ascii "# file:loop.c line:15 function:main\n"
73 .byte 7,8
74 .quad .L104
75 .ascii " _Gamma_0: reg(\"rdx\") -> LOW, reg(\"rdi\") -> LOW\n"
76 .ascii "# file:loop.c line:19 function:main\n"
77 .byte 7,8
78 .quad .L106
79 .ascii " _invariant: reg(\"rdx\") % 2 == 0 & reg(\"rdx\") <= mem("
80 .byte 7,8
81 .quad z
82 .ascii ", 4)\n"
83 .ascii "# file:loop.c line:20 function:main\n"
84 .byte 7,8
85 .quad .L107
86 .ascii " _Gamma: reg(\"rdx\") -> LOW, reg(\"rdi\") -> (reg(\"rdx\") == mem("
87 .byte 7,8
88 .quad z
89 .ascii ", 4)), mem("
90 .byte 7,8
91 .quad z
92 .ascii ", 4) -> LOW\n"
93 .ascii "# file:loop.c line:22 function:main\n"
94 .byte 7,8
95 .quad .L109
96 .ascii " _invariant: reg(\"rdx\") <= mem("
97 .byte 7,8

```

```

98 .quad z
99 .ascii ", 4)\n"
100 .ascii "# file:loop.c line:23 function:main\n"
101 .byte 7,8
102 .quad .L110
103 .ascii " _Gamma: reg(\"rdx\") -> LOW\n"

```

C.8 loop-O3.s

```

1 # File generated by CompCert 3.7
2 # Command line: loop.c -O3 -S
3 .comm z, 4, 4
4 .comm x, 4, 4
5 .text
6 .align 16
7 .globl main
8 main:
9 .cfi_startproc
10 subq $8, %rsp
11 .cfi_adjust_cfa_offset 8
12 leaq 16(%rsp), %rax
13 movq %rax, 0(%rsp)
14 .L100:
15 .L101:
16 xorl %edx, %edx
17 xorl %edi, %edi
18 .L102:
19 .L103:
20 .L104:
21 nop
22 .L105:
23 .L106:
24 .L107:
25 nop
26 .L108:
27 .L109:
28 .L110:
29 movl z(%rip), %edx
30 movq %rdx, %rax
31 testl %eax, %eax
32 leal 1(%eax), %ecx
33 cmovl %rcx, %rax
34 sarl $1, %eax
35 leal 0(,%eax,2), %edi
36 movq %rdx, %rcx
37 subl %edi, %ecx
38 testl %ecx, %ecx
39 jne .L108
40 movl x(%rip), %edi
41 movq %rdx, %rsi
42 jmp .L105
43 .cfi_endproc
44 .type main, @function
45 .size main, . - main
46 .section "__compcert_ais_annotations","",@note
47 .ascii "# file:loop.c line:7 function:main\n"
48 .byte 7,8

```

```

49 .quad .L100
50 .ascii " L(mem("
51 .byte 7,8
52 .quad z
53 .ascii ", 4)) = true\n"
54 .ascii "# file:loop.c line:8 function:main\n"
55 .byte 7,8
56 .quad .L101
57 .ascii " L(mem("
58 .byte 7,8
59 .quad x
60 .ascii ", 4))= mem("
61 .byte 7,8
62 .quad z
63 .ascii ", 4) % 2 == 0\n"
64 .ascii "# file:loop.c line:11 function:main\n"
65 .byte 7,8
66 .quad .L102
67 .ascii " L(0)= false\n"
68 .ascii "# file:loop.c line:14 function:main\n"
69 .byte 7,8
70 .quad .L103
71 .ascii " _P_0: 0 % 2 == 0\n"
72 .ascii "# file:loop.c line:15 function:main\n"
73 .byte 7,8
74 .quad .L104
75 .ascii " _Gamma_0: 0 -> LOW, 0 -> LOW\n"
76 .ascii "# file:loop.c line:19 function:main\n"
77 .byte 7,8
78 .quad .L106
79 .ascii " _invariant: reg(\"rdx\") % 2 == 0 & reg(\"rdx\") <= mem("
80 .byte 7,8
81 .quad z
82 .ascii ", 4)\n"
83 .ascii "# file:loop.c line:20 function:main\n"
84 .byte 7,8
85 .quad .L107
86 .ascii " _Gamma: reg(\"rdx\") -> LOW, reg(\"rdi\") -> (reg(\"rdx\") == mem("
87 .byte 7,8
88 .quad z
89 .ascii ", 4)), mem("
90 .byte 7,8
91 .quad z
92 .ascii ", 4) -> LOW\n"
93 .ascii "# file:loop.c line:22 function:main\n"
94 .byte 7,8
95 .quad .L109
96 .ascii " _invariant: reg(\"rdx\") <= mem("
97 .byte 7,8
98 .quad z
99 .ascii ", 4)\n"
100 .ascii "# file:loop.c line:23 function:main\n"
101 .byte 7,8
102 .quad .L110
103 .ascii " _Gamma: reg(\"rdx\") -> LOW\n"

```

C.9 rooster-O0.s

```

1 # File generated by CompCert 3.7
2 # Command line: rooster.c -O0 -S
3 .comm rooster, 4, 4
4 .comm drake, 4, 4
5 .comm goose, 4, 4
6 .data
7 .align 4
8 count:
9 .long 0
10 .type count, @object
11 .size count, . - count
12 .text
13 .align 16
14 .globl fun
15 fun:
16 .cfi_startproc
17 subq $8, %rsp
18 .cfi_adjust_cfa_offset 8
19 leaq 16(%rsp), %rax
20 movq %rax, 0(%rsp)
21 .L100:
22 leal 0(%edi,%esi,1), %r8d
23 leal 0(%r8d,%edx,1), %eax
24 testl %eax, %eax
25 jl .L101
26 cmpl %esi, %edi
27 jl .L102
28 xorl %r8d, %r8d
29 jmp .L103
30 .L102:
31 cmpl %edx, %esi
32 setl %r8b
33 movzbl %r8b, %r8d
34 .L103:
35 cmpl $0, %r8d
36 je .L104
37 .L105:
38 cmpl %esi, %edi
39 je .L104
40 leal 1(%edi), %edi
41 movl count(%rip), %eax
42 leal 1(%eax), %ecx
43 movl %ecx, count(%rip)
44 .L106:
45 cmpl %edx, %esi
46 je .L105
47 leal -1(%edx), %edx
48 movl count(%rip), %r9d
49 leal 1(%r9d), %r8d
50 movl %r8d, count(%rip)
51 jmp .L106
52 .L104:
53 movl count(%rip), %eax
54 .L101:
55 addq $8, %rsp
56 ret
57 .cfi_endproc

```

```

58 .type fun, @function
59 .size fun, . - fun
60 .text
61 .align 16
62 .globl main
63 main:
64 .cfi_startproc
65 subq $8, %rsp
66 .cfi_adjust_cfa_offset 8
67 leaq 16(%rsp), %rax
68 movq %rax, 0(%rsp)
69 .L107:
70 .L108:
71 movl $1, %eax
72 movl %eax, rooster(%rip)
73 movl $5, %eax
74 movl %eax, drake(%rip)
75 movl $10, %eax
76 movl %eax, goose(%rip)
77 movl rooster(%rip), %edi
78 movl drake(%rip), %esi
79 movl goose(%rip), %edx
80 call fun
81 xorl %eax, %eax
82 addq $8, %rsp
83 ret
84 .cfi_endproc
85 .type main, @function
86 .size main, . - main
87 .section "__compcert_ais_annotations","",@note
88 .ascii "# file:rooster.c line:6 function:fun\n"
89 .byte 7,8
90 .quad .L100
91 .ascii " CRITICAL COMMENT\n"
92 .ascii "# file:rooster.c line:26 function:main\n"
93 .byte 7,8
94 .quad .L107
95 .ascii " L(mem("
96 .byte 7,8
97 .quad goose
98 .ascii ", 4)) = medium\n"
99 .ascii "# file:rooster.c line:27 function:main\n"
100 .byte 7,8
101 .quad .L108
102 .ascii " EXCEPTIONAL\n"

```

C.10 rooster-O3.s

```

1 # File generated by CompCert 3.7
2 # Command line: rooster.c -O3 -S
3 .comm rooster, 4, 4
4 .comm drake, 4, 4
5 .comm goose, 4, 4
6 .data
7 .align 4
8 count:
9 .long 0

```

```

10 .type count, @object
11 .size count, . - count
12 .text
13 .align 16
14 .globl fun
15 fun:
16 .cfi_startproc
17 subq $8, %rsp
18 .cfi_adjust_cfa_offset 8
19 leaq 16(%rsp), %rax
20 movq %rax, 0(%rsp)
21 .L100:
22 leal 0(%edi,%esi,1), %r9d
23 leal 0(%r9d,%edx,1), %eax
24 testl %eax, %eax
25 jl .L101
26 cmpl %edx, %esi
27 setl %al
28 movzbl %al, %eax
29 xorl %r8d, %r8d
30 cmpl %esi, %edi
31 cmovge %r8, %rax
32 cmpl $0, %eax
33 je .L102
34 .L103:
35 cmpl %esi, %edi
36 je .L102
37 leal 1(%edi), %edi
38 movl count(%rip), %ecx
39 leal 1(%ecx), %r8d
40 movl %r8d, count(%rip)
41 .L104:
42 cmpl %edx, %esi
43 je .L103
44 leal -1(%edx), %edx
45 movl count(%rip), %r10d
46 leal 1(%r10d), %r8d
47 movl %r8d, count(%rip)
48 jmp .L104
49 .L102:
50 movl count(%rip), %eax
51 .L101:
52 addq $8, %rsp
53 ret
54 .cfi_endproc
55 .type fun, @function
56 .size fun, . - fun
57 .text
58 .align 16
59 .globl main
60 main:
61 .cfi_startproc
62 subq $8, %rsp
63 .cfi_adjust_cfa_offset 8
64 leaq 16(%rsp), %rax
65 movq %rax, 0(%rsp)
66 .L105:

```



```

67 .L106:
68     movl    $1, %eax
69     movl    %eax, rooster(%rip)
70     movl    $5, %eax
71     movl    %eax, drake(%rip)
72     movl    $10, %eax
73     movl    %eax, goose(%rip)
74     movl    $1, %edi
75     movl    $5, %esi
76     movl    $10, %edx
77     call    fun
78     xorl    %eax, %eax
79     addq    $8, %rsp
80     ret
81     .cfi_endproc
82     .type   main, @function
83     .size   main, . - main
84     .section "__compcert_ais_annotations","",@note
85     .ascii  "# file:rooster.c line:6 function:fun\n"
86     .byte   7,8
87     .quad   .L100
88     .ascii  " CRITICAL COMMENT\n"
89     .ascii  "# file:rooster.c line:26 function:main\n"
90     .byte   7,8
91     .quad   .L105
92     .ascii  " L(mem("
93     .byte   7,8
94     .quad   goose
95     .ascii  ", 4)) = medium\n"
96     .ascii  "# file:rooster.c line:27 function:main\n"
97     .byte   7,8
98     .quad   .L106
99     .ascii  " EXCEPTIONAL\n"

```

C.11 password-O0.s

```

1 # File generated by CompCert 3.7
2 # Command line: password.c -O0 -S
3     .section .rodata
4     .align 1
5 __stringlit_7:
6     .ascii  "--- USERS ---\012\000"
7     .type   __stringlit_7, @object
8     .size   __stringlit_7, . - __stringlit_7
9     .section .rodata
10    .align 1
11 __stringlit_6:
12    .ascii  "passwOrd123\000"
13    .type   __stringlit_6, @object
14    .size   __stringlit_6, . - __stringlit_6
15    .section .rodata
16    .align 1
17 __stringlit_4:
18    .ascii  "!alice12!_veujs@hak\000"
19    .type   __stringlit_4, @object
20    .size   __stringlit_4, . - __stringlit_4
21    .section .rodata

```

```

22 .align 1
23 __stringlit_14:
24 .ascii "Password: \000"
25 .type __stringlit_14, @object
26 .size __stringlit_14, . - __stringlit_14
27 .section .rodata
28 .align 1
29 __stringlit_18:
30 .ascii "Your balance: $%ld\012\000"
31 .type __stringlit_18, @object
32 .size __stringlit_18, . - __stringlit_18
33 .section .rodata
34 .align 1
35 __stringlit_13:
36 .ascii "User < %s > does not exist.\012\000"
37 .type __stringlit_13, @object
38 .size __stringlit_13, . - __stringlit_13
39 .section .rodata
40 .align 1
41 __stringlit_8:
42 .ascii " %02ld. %s\012\000"
43 .type __stringlit_8, @object
44 .size __stringlit_8, . - __stringlit_8
45 .section .rodata
46 .align 1
47 __stringlit_1:
48 .ascii "admin\000"
49 .type __stringlit_1, @object
50 .size __stringlit_1, . - __stringlit_1
51 .section .rodata
52 .align 1
53 __stringlit_2:
54 .ascii "4dmin__4eva\000"
55 .type __stringlit_2, @object
56 .size __stringlit_2, . - __stringlit_2
57 .section .rodata
58 .align 1
59 __stringlit_3:
60 .ascii "alice\000"
61 .type __stringlit_3, @object
62 .size __stringlit_3, . - __stringlit_3
63 .section .rodata
64 .align 1
65 __stringlit_11:
66 .ascii "Username: \000"
67 .type __stringlit_11, @object
68 .size __stringlit_11, . - __stringlit_11
69 .section .rodata
70 .align 1
71 __stringlit_5:
72 .ascii "abdul\000"
73 .type __stringlit_5, @object
74 .size __stringlit_5, . - __stringlit_5
75 .section .rodata
76 .align 1
77 __stringlit_17:
78 .ascii "Welcome, %s!\012\000"

```

```

79 .type __stringlit_17, @object
80 .size __stringlit_17, . - __stringlit_17
81 .section .rodata
82 .align 1
83 __stringlit_12:
84 .ascii "%255s\000"
85 .type __stringlit_12, @object
86 .size __stringlit_12, . - __stringlit_12
87 .section .rodata
88 .align 1
89 __stringlit_9:
90 .ascii "\012\000"
91 .type __stringlit_9, @object
92 .size __stringlit_9, . - __stringlit_9
93 .section .rodata
94 .align 1
95 __stringlit_15:
96 .ascii "ERROR: incorrect password\012\000"
97 .type __stringlit_15, @object
98 .size __stringlit_15, . - __stringlit_15
99 .section .rodata
100 .align 1
101 __stringlit_10:
102 .ascii "Welcome to BigBank Australia!\012\000"
103 .type __stringlit_10, @object
104 .size __stringlit_10, . - __stringlit_10
105 .section .rodata
106 .align 1
107 __stringlit_16:
108 .ascii "Logged in as < %s >!\012\000"
109 .type __stringlit_16, @object
110 .size __stringlit_16, . - __stringlit_16
111 .text
112 .align 16
113 .globl setup_users
114 setup_users:
115 .cfi_startproc
116 subq $40, %rsp
117 .cfi_adjust_cfa_offset 40
118 leaq 48(%rsp), %rax
119 movq %rax, 0(%rsp)
120 movq %rbx, 8(%rsp)
121 movq %rbp, 16(%rsp)
122 movq %r12, 24(%rsp)
123 movq $528, %rdi
124 call malloc
125 movq %rax, %rbp
126 leaq 8(%rbp), %rdi
127 leaq __stringlit_1(%rip), %rsi
128 call strcpy
129 leaq 264(%rbp), %rdi
130 leaq __stringlit_2(%rip), %rsi
131 call strcpy
132 .L100:
133 movq $1000000, %r10
134 movq %r10, 520(%rbp)
135 movq $528, %rdi

```

```

136  call    malloc
137  movq    %rax, %r12
138  leaq    8(%r12), %rdi
139  leaq    __stringlit_3(%rip), %rsi
140  call    strcpy
141  leaq    264(%r12), %rdi
142  leaq    __stringlit_4(%rip), %rsi
143  call    strcpy
144  .L101:
145  movq    $783, %r9
146  movq    %r9, 520(%r12)
147  movq    $528, %rdi
148  call    malloc
149  movq    %rax, %rbx
150  leaq    8(%rbx), %rdi
151  leaq    __stringlit_5(%rip), %rsi
152  call    strcpy
153  leaq    264(%rbx), %rdi
154  leaq    __stringlit_6(%rip), %rsi
155  call    strcpy
156  .L102:
157  movq    $2, %r11
158  movq    %r11, 520(%rbx)
159  movq    %r12, 0(%rbp)
160  movq    %rbx, 0(%r12)
161  xorq    %r8, %r8
162  movq    %r8, 0(%rbx)
163  movq    %rbp, %rax
164  movq    8(%rsp), %rbx
165  movq    16(%rsp), %rbp
166  movq    24(%rsp), %r12
167  addq    $40, %rsp
168  ret
169  .cfi_endproc
170  .type   setup_users, @function
171  .size   setup_users, . - setup_users
172  .text
173  .align  16
174  .globl  print_users
175  print_users:
176  .cfi_startproc
177  subq    $24, %rsp
178  .cfi_adjust_cfa_offset 24
179  leaq    32(%rsp), %rax
180  movq    %rax, 0(%rsp)
181  movq    %rbx, 8(%rsp)
182  movq    %rbp, 16(%rsp)
183  movq    %rdi, %rbx
184  leaq    __stringlit_7(%rip), %rdi
185  movl    $0, %eax
186  call    printf
187  xorq    %rbp, %rbp
188  .L103:
189  cmpq    $0, %rbx
190  je      .L104
191  leaq    1(%rbp), %rbp
192  leaq    __stringlit_8(%rip), %rdi

```

```

193 leaq 8(%rbx), %rdx
194 movq %rbp, %rsi
195 movl $0, %eax
196 call printf
197 movq 0(%rbx), %rbx
198 jmp .L103
199 .L104:
200 leaq __stringlit_9(%rip), %rdi
201 movl $0, %eax
202 call printf
203 movq 8(%rsp), %rbx
204 movq 16(%rsp), %rbp
205 addq $24, %rsp
206 ret
207 .cfi_endproc
208 .type print_users, @function
209 .size print_users, . - print_users
210 .text
211 .align 16
212 .globl getUser
213 getUser:
214 .cfi_startproc
215 subq $24, %rsp
216 .cfi_adjust_cfa_offset 24
217 leaq 32(%rsp), %rax
218 movq %rax, 0(%rsp)
219 movq %rbx, 8(%rsp)
220 movq %rbp, 16(%rsp)
221 movq %rsi, %rbp
222 movq %rdi, %rbx
223 .L105:
224 cmpq $0, %rbx
225 je .L106
226 leaq 8(%rbx), %rdi
227 movq %rbp, %rsi
228 call strcmp
229 testl %eax, %eax
230 je .L107
231 movq 0(%rbx), %rbx
232 jmp .L105
233 .L106:
234 xorq %rbx, %rbx
235 .L107:
236 movq %rbx, %rax
237 movq 8(%rsp), %rbx
238 movq 16(%rsp), %rbp
239 addq $24, %rsp
240 ret
241 .cfi_endproc
242 .type getUser, @function
243 .size getUser, . - getUser
244 .text
245 .align 16
246 .globl main
247 main:
248 .cfi_startproc
249 subq $536, %rsp

```

```

250 .cfi_adjust_cfa_offset 536
251 leaq 544(%rsp), %rax
252 movq %rax, 0(%rsp)
253 movq %rbx, 8(%rsp)
254 call setup_users
255 movq %rax, %rbx
256 leaq __stringlit_10(%rip), %rdi
257 movl $0, %eax
258 call printf
259 leaq __stringlit_11(%rip), %rdi
260 movl $0, %eax
261 call printf
262 leaq __stringlit_12(%rip), %rdi
263 leaq 16(%rsp), %rsi
264 movl $0, %eax
265 call __isoc99_scanf
266 leaq 16(%rsp), %rsi
267 movq %rbx, %rdi
268 call getUser
269 movq %rax, %rbx
270 cmpq $0, %rbx
271 jne .L108
272 leaq __stringlit_13(%rip), %rdi
273 leaq 16(%rsp), %rsi
274 movl $0, %eax
275 call printf
276 xorl %eax, %eax
277 jmp .L109
278 .L108:
279 leaq __stringlit_14(%rip), %rdi
280 movl $0, %eax
281 call printf
282 leaq __stringlit_12(%rip), %rdi
283 leaq 272(%rsp), %rsi
284 movl $0, %eax
285 call __isoc99_scanf
286 leaq 264(%rbx), %rdi
287 leaq 272(%rsp), %rsi
288 call strcmp
289 testl %eax, %eax
290 je .L110
291 leaq __stringlit_15(%rip), %rdi
292 movl $0, %eax
293 call printf
294 xorl %eax, %eax
295 jmp .L109
296 .L110:
297 leaq __stringlit_16(%rip), %rdi
298 leaq 8(%rbx), %rsi
299 movl $0, %eax
300 call printf
301 leaq __stringlit_9(%rip), %rdi
302 movl $0, %eax
303 call printf
304 leaq __stringlit_17(%rip), %rdi
305 leaq 8(%rbx), %rsi
306 movl $0, %eax

```

```

307  call    printf
308  leaq    __stringlit_18(%rip), %rdi
309  movq    520(%rbx), %rsi
310  movl    $0, %eax
311  call    printf
312  xorl    %eax, %eax
313  .L109:
314  movq    8(%rsp), %rbx
315  addq    $536, %rsp
316  ret
317  .cfi_endproc
318  .type   main, @function
319  .size   main, . - main
320  .section "__compcert_ais_annotations","",@note
321  .ascii  " # file:password.c line:20 function:setup_users\n"
322  .byte   7,8
323  .quad   .L100
324  .ascii  " L((reg(\"rbp\") + 264)) = high\n"
325  .ascii  " # file:password.c line:26 function:setup_users\n"
326  .byte   7,8
327  .quad   .L101
328  .ascii  " L((reg(\"r12\") + 264)) = high\n"
329  .ascii  " # file:password.c line:32 function:setup_users\n"
330  .byte   7,8
331  .quad   .L102
332  .ascii  " L((reg(\"rbx\") + 264)) = high\n"

```

C.12 password-O3.s

```

1  # File generated by CompCert 3.7
2  # Command line: password.c -O3 -S
3  .section .rodata
4  .align 1
5  __stringlit_7:
6  .ascii  "--- USERS ---\012\000"
7  .type   __stringlit_7, @object
8  .size   __stringlit_7, . - __stringlit_7
9  .section .rodata
10 .align 1
11 __stringlit_6:
12 .ascii  "passwOrd123\000"
13 .type   __stringlit_6, @object
14 .size   __stringlit_6, . - __stringlit_6
15 .section .rodata
16 .align 1
17 __stringlit_4:
18 .ascii  "!alice12!_veu je@@hak\000"
19 .type   __stringlit_4, @object
20 .size   __stringlit_4, . - __stringlit_4
21 .section .rodata
22 .align 1
23 __stringlit_14:
24 .ascii  "Password: \000"
25 .type   __stringlit_14, @object
26 .size   __stringlit_14, . - __stringlit_14
27 .section .rodata
28 .align 1

```

```

29 __stringlit_18:
30     .ascii  "Your balance: $%ld\012\000"
31     .type   __stringlit_18, @object
32     .size   __stringlit_18, . - __stringlit_18
33     .section .rodata
34     .align  1
35 __stringlit_13:
36     .ascii  "User < %s > does not exist.\012\000"
37     .type   __stringlit_13, @object
38     .size   __stringlit_13, . - __stringlit_13
39     .section .rodata
40     .align  1
41 __stringlit_8:
42     .ascii  "%02ld. %s\012\000"
43     .type   __stringlit_8, @object
44     .size   __stringlit_8, . - __stringlit_8
45     .section .rodata
46     .align  1
47 __stringlit_1:
48     .ascii  "admin\000"
49     .type   __stringlit_1, @object
50     .size   __stringlit_1, . - __stringlit_1
51     .section .rodata
52     .align  1
53 __stringlit_2:
54     .ascii  "4dmin__4eva\000"
55     .type   __stringlit_2, @object
56     .size   __stringlit_2, . - __stringlit_2
57     .section .rodata
58     .align  1
59 __stringlit_3:
60     .ascii  "alice\000"
61     .type   __stringlit_3, @object
62     .size   __stringlit_3, . - __stringlit_3
63     .section .rodata
64     .align  1
65 __stringlit_11:
66     .ascii  "Username: \000"
67     .type   __stringlit_11, @object
68     .size   __stringlit_11, . - __stringlit_11
69     .section .rodata
70     .align  1
71 __stringlit_5:
72     .ascii  "abdul\000"
73     .type   __stringlit_5, @object
74     .size   __stringlit_5, . - __stringlit_5
75     .section .rodata
76     .align  1
77 __stringlit_17:
78     .ascii  "Welcome, %s!\012\000"
79     .type   __stringlit_17, @object
80     .size   __stringlit_17, . - __stringlit_17
81     .section .rodata
82     .align  1
83 __stringlit_12:
84     .ascii  "%255s\000"
85     .type   __stringlit_12, @object

```



```

86 .size __stringlit_12, . - __stringlit_12
87 .section .rodata
88 .align 1
89 __stringlit_9:
90 .ascii "\012\000"
91 .type __stringlit_9, @object
92 .size __stringlit_9, . - __stringlit_9
93 .section .rodata
94 .align 1
95 __stringlit_15:
96 .ascii "ERROR: incorrect password\012\000"
97 .type __stringlit_15, @object
98 .size __stringlit_15, . - __stringlit_15
99 .section .rodata
100 .align 1
101 __stringlit_10:
102 .ascii "Welcome to BigBank Australia!\012\000"
103 .type __stringlit_10, @object
104 .size __stringlit_10, . - __stringlit_10
105 .section .rodata
106 .align 1
107 __stringlit_16:
108 .ascii "Logged in as < %s >!\012\000"
109 .type __stringlit_16, @object
110 .size __stringlit_16, . - __stringlit_16
111 .text
112 .align 16
113 .globl setup_users
114 setup_users:
115 .cfi_startproc
116 subq $40, %rsp
117 .cfi_adjust_cfa_offset 40
118 leaq 48(%rsp), %rax
119 movq %rax, 0(%rsp)
120 movq %rbx, 8(%rsp)
121 movq %rbp, 16(%rsp)
122 movq %r12, 24(%rsp)
123 movq $528, %rdi
124 call malloc
125 movq %rax, %rbp
126 leaq 8(%rbp), %rdi
127 leaq __stringlit_1(%rip), %rsi
128 call strcpy
129 leaq 264(%rbp), %rdi
130 leaq __stringlit_2(%rip), %rsi
131 call strcpy
132 .L100:
133 movq $1000000, %r10
134 movq %r10, 520(%rbp)
135 movq $528, %rdi
136 call malloc
137 movq %rax, %r12
138 leaq 8(%r12), %rdi
139 leaq __stringlit_3(%rip), %rsi
140 call strcpy
141 leaq 264(%r12), %rdi
142 leaq __stringlit_4(%rip), %rsi

```

```

143     call    strcpy
144 .L101:
145     movq    $783, %r9
146     movq    %r9, 520(%r12)
147     movq    $528, %rdi
148     call    malloc
149     movq    %rax, %rbx
150     leaq    8(%rbx), %rdi
151     leaq    __stringlit_5(%rip), %rsi
152     call    strcpy
153     leaq    264(%rbx), %rdi
154     leaq    __stringlit_6(%rip), %rsi
155     call    strcpy
156 .L102:
157     movq    $2, %r11
158     movq    %r11, 520(%rbx)
159     movq    %r12, 0(%rbp)
160     movq    %rbx, 0(%r12)
161     xorq    %r8, %r8
162     movq    %r8, 0(%rbx)
163     movq    %rbp, %rax
164     movq    8(%rsp), %rbx
165     movq    16(%rsp), %rbp
166     movq    24(%rsp), %r12
167     addq    $40, %rsp
168     ret
169     .cfi_endproc
170     .type   setup_users, @function
171     .size   setup_users, . - setup_users
172     .text
173     .align  16
174     .globl  print_users
175 print_users:
176     .cfi_startproc
177     subq    $24, %rsp
178     .cfi_adjust_cfa_offset 24
179     leaq    32(%rsp), %rax
180     movq    %rax, 0(%rsp)
181     movq    %rbx, 8(%rsp)
182     movq    %rbp, 16(%rsp)
183     movq    %rdi, %rbp
184     leaq    __stringlit_7(%rip), %rdi
185     movl    $0, %eax
186     call    printf
187     xorq    %rbx, %rbx
188 .L103:
189     cmpq    $0, %rbp
190     je      .L104
191     leaq    1(%rbx), %rbx
192     leaq    __stringlit_8(%rip), %rdi
193     leaq    8(%rbp), %rdx
194     movq    %rbx, %rsi
195     movl    $0, %eax
196     call    printf
197     movq    0(%rbp), %rbp
198     jmp     .L103
199 .L104:

```

```

200 leaq __stringlit_9(%rip), %rdi
201 movl $0, %eax
202 call printf
203 movq 8(%rsp), %rbx
204 movq 16(%rsp), %rbp
205 addq $24, %rsp
206 ret
207 .cfi_endproc
208 .type print_users, @function
209 .size print_users, . - print_users
210 .text
211 .align 16
212 .globl getUser
213 getUser:
214 .cfi_startproc
215 subq $24, %rsp
216 .cfi_adjust_cfa_offset 24
217 leaq 32(%rsp), %rax
218 movq %rax, 0(%rsp)
219 movq %rbx, 8(%rsp)
220 movq %rbp, 16(%rsp)
221 movq %rsi, %rbp
222 movq %rdi, %rbx
223 .L105:
224 cmpq $0, %rbx
225 je .L106
226 leaq 8(%rbx), %rdi
227 movq %rbp, %rsi
228 call strcmp
229 testl %eax, %eax
230 je .L107
231 movq 0(%rbx), %rbx
232 jmp .L105
233 .L106:
234 xorq %rbx, %rbx
235 .L107:
236 movq %rbx, %rax
237 movq 8(%rsp), %rbx
238 movq 16(%rsp), %rbp
239 addq $24, %rsp
240 ret
241 .cfi_endproc
242 .type getUser, @function
243 .size getUser, . - getUser
244 .text
245 .align 16
246 .globl main
247 main:
248 .cfi_startproc
249 subq $536, %rsp
250 .cfi_adjust_cfa_offset 536
251 leaq 544(%rsp), %rax
252 movq %rax, 0(%rsp)
253 movq %rbx, 8(%rsp)
254 call setup_users
255 movq %rax, %rbx
256 leaq __stringlit_10(%rip), %rdi

```

```

257 movl $0, %eax
258 call printf
259 leaq __stringlit_11(%rip), %rdi
260 movl $0, %eax
261 call printf
262 leaq __stringlit_12(%rip), %rdi
263 leaq 16(%rsp), %rsi
264 movl $0, %eax
265 call __isoc99_scanf
266 leaq 16(%rsp), %rsi
267 movq %rbx, %rdi
268 call getUser
269 movq %rax, %rbx
270 cmpq $0, %rbx
271 jne .L108
272 leaq __stringlit_13(%rip), %rdi
273 leaq 16(%rsp), %rsi
274 movl $0, %eax
275 call printf
276 xorl %eax, %eax
277 jmp .L109
278 .L108:
279 leaq __stringlit_14(%rip), %rdi
280 movl $0, %eax
281 call printf
282 leaq __stringlit_12(%rip), %rdi
283 leaq 272(%rsp), %rsi
284 movl $0, %eax
285 call __isoc99_scanf
286 leaq 264(%rbx), %rdi
287 leaq 272(%rsp), %rsi
288 call strcmp
289 testl %eax, %eax
290 je .L110
291 leaq __stringlit_15(%rip), %rdi
292 movl $0, %eax
293 call printf
294 xorl %eax, %eax
295 jmp .L109
296 .L110:
297 leaq __stringlit_16(%rip), %rdi
298 leaq 8(%rbx), %rsi
299 movl $0, %eax
300 call printf
301 leaq __stringlit_9(%rip), %rdi
302 movl $0, %eax
303 call printf
304 leaq __stringlit_17(%rip), %rdi
305 leaq 8(%rbx), %rsi
306 movl $0, %eax
307 call printf
308 leaq __stringlit_18(%rip), %rdi
309 movq 520(%rbx), %rsi
310 movl $0, %eax
311 call printf
312 xorl %eax, %eax
313 .L109:

```

```

314 movq 8(%rsp), %rbx
315 addq $536, %rsp
316 ret
317 .cfi_endproc
318 .type main, @function
319 .size main, . - main
320 .section "__compcert_ais_annotations","",@note
321 .ascii "# file:password.c line:20 function:setup_users\n"
322 .byte 7,8
323 .quad .L100
324 .ascii " L((reg(\"rbp\") + 264)) = high\n"
325 .ascii "# file:password.c line:26 function:setup_users\n"
326 .byte 7,8
327 .quad .L101
328 .ascii " L((reg(\"r12\") + 264)) = high\n"
329 .ascii "# file:password.c line:32 function:setup_users\n"
330 .byte 7,8
331 .quad .L102
332 .ascii " L((reg(\"rbx\") + 264)) = high\n"

```

C.13 deadStoreElimination-O0.s

```

1 # File generated by CompCert 3.7
2 # Command line: deadStoreElimination.c -O0 -S
3 .text
4 .align 16
5 .globl deadStore
6 deadStore:
7 .cfi_startproc
8 subq $8, %rsp
9 .cfi_adjust_cfa_offset 8
10 leaq 16(%rsp), %rax
11 movq %rax, 0(%rsp)
12 movl $43981, %ecx
13 .L100:
14 nop
15 .L101:
16 cmpl %esi, %edi
17 jle .L102
18 leal -1(%edi), %edi
19 jmp .L101
20 .L102:
21 leal 0(%edi,%esi,1), %eax
22 addq $8, %rsp
23 ret
24 .cfi_endproc
25 .type deadStore, @function
26 .size deadStore, . - deadStore
27 .text
28 .align 16
29 .globl main
30 main:
31 .cfi_startproc
32 subq $8, %rsp
33 .cfi_adjust_cfa_offset 8
34 leaq 16(%rsp), %rax
35 movq %rax, 0(%rsp)

```

```

36  movl  $2, %esi
37  call  deadStore
38  xorl  %eax, %eax
39  addq  $8, %rsp
40  ret
41  .cfi_endproc
42  .type  main, @function
43  .size  main, . - main
44  .section  "__compcert_ais_annotations","",@note
45  .ascii  "# file:deadStoreElimination.c line:3 function:deadStore\n"
46  .byte  7,8
47  .quad  .L100
48  .ascii  " L(reg(\"rcx\")) = high\n"

```

C.14 deadStoreElimination-O3.s

```

1  # File generated by CompCert 3.7
2  # Command line: deadStoreElimination.c -O3 -S
3  .text
4  .align 16
5  .globl deadStore
6  deadStore:
7  .cfi_startproc
8  subq  $8, %rsp
9  .cfi_adjust_cfa_offset 8
10 leaq  16(%rsp), %rax
11 movq  %rax, 0(%rsp)
12 .L100:
13  nop
14 .L101:
15  cmpl  %esi, %edi
16  jle  .L102
17  leal  -1(%edi), %edi
18  jmp  .L101
19 .L102:
20  leal  0(%edi,%esi,1), %eax
21  addq  $8, %rsp
22  ret
23  .cfi_endproc
24  .type  deadStore, @function
25  .size  deadStore, . - deadStore
26  .text
27  .align 16
28  .globl main
29  main:
30  .cfi_startproc
31  subq  $8, %rsp
32  .cfi_adjust_cfa_offset 8
33  leaq  16(%rsp), %rax
34  movq  %rax, 0(%rsp)
35  movl  $2, %esi
36  call  deadStore
37  xorl  %eax, %eax
38  addq  $8, %rsp
39  ret
40  .cfi_endproc
41  .type  main, @function

```

```

42 .size main, . - main
43 .section "__compcert_ais_annotations","",@note
44 .ascii "# file:deadStoreElimination.c line:3 function:deadStore\n"
45 .byte 7,8
46 .quad .L100
47 .ascii " L(43981) = high\n"

```

C.15 pread-O0.s

```

1 pread.c:6: error: access to volatile variable 'z' for parameter '%e1' is not supported in
  ais annotations
2 pread.c:7: error: access to volatile variable 'x' for parameter '%e1' is not supported in
  ais annotations
3 pread.c:7: error: access to volatile variable 'z' for parameter '%e2' is not supported in
  ais annotations
4 pread.c:20: error: access to volatile variable 'z' for parameter '%e2' is not supported in
  ais annotations
5 pread.c:21: error: access to volatile variable 'z' for parameter '%e3' is not supported in
  ais annotations
6 pread.c:21: error: access to volatile variable 'z' for parameter '%e3' is not supported in
  ais annotations
7 pread.c:23: error: access to volatile variable 'z' for parameter '%e2' is not supported in
  ais annotations
8 7 errors detected.

```

C.16 pread-O3.s

```

1 pread.c:6: error: access to volatile variable 'z' for parameter '%e1' is not supported in
  ais annotations
2 pread.c:7: error: access to volatile variable 'x' for parameter '%e1' is not supported in
  ais annotations
3 pread.c:7: error: access to volatile variable 'z' for parameter '%e2' is not supported in
  ais annotations
4 pread.c:20: error: access to volatile variable 'z' for parameter '%e2' is not supported in
  ais annotations
5 pread.c:21: error: access to volatile variable 'z' for parameter '%e3' is not supported in
  ais annotations
6 pread.c:21: error: access to volatile variable 'z' for parameter '%e3' is not supported in
  ais annotations
7 pread.c:23: error: access to volatile variable 'z' for parameter '%e2' is not supported in
  ais annotations
8 7 errors detected.

```