FUNQUAL: USER-DEFINED, STATICALLY-CHECKED CALL-TREE CONSTRAINTS IN C++

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ABSTRACT

Funqual: User-Defined, Statically-Checked Call-Tree Constraints in C++

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Static analysis tools can aid programmers by reporting potential programming mistakes prior to the execution of a program. Funqual is a static analysis tool that reads C++17 code "in the wild" and checks that the function call graph follows a set of rules which can be defined by the user. This sort of analysis can help the programmer to avoid errors such as accidentally calling blocking functions in time-sensitive contexts or accidentally allocating memory in heap-sensitive environments. To accomplish this, we create a type system whereby functions can be given user-defined type qualifiers and where users can define their own restrictions on the call tree based on these type qualifiers. We demonstrate that this tool, when used with hand-crafted rules, can catch certain types of errors which commonly occur in the wild. We claim that this tool can be used in a production setting to catch certain kinds of errors in code before that code is even run.

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- Dennis Ritchie and Bjarne Stroustrup. You've accidentally created something hauntingly expressive, painstakingly verbose, geniusly strict, and idiotically sloppy. C++17 is a hot mess but it's everwhere - thank God it's type safe.

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INTRODUCTION

Writing bug-free software is challenging if not impossible. In the past 30 years, millions of dollars have been invested in tools that help developers write code that is robust, readable, and correct [14]. In general these tools fall into two categories: Dynamic Analysis tools such as gdb, valgrind, and IDA which analyze programs as they are running; and Static Analysis tools such as lint, cppcheck, and GCC -WAll. All these tools have different use cases and can be used in conjunction to minimize the presence of errors in code.

While these tools are extremely helpful in finding bugs in code, they are by no means complete. Every tool uses a finite set of techniques to detect a specific class of issues. Some tools examine the types of values and expressions to enforce type safety[14], some tools examine ownership of objects to enforce memory safety[8], some tools examine the flow of values through a program to ensure security[6], and many other tools do other things entirely.

This paper intends to add a new technique to the existing arsenal making it possible to check for errors which were previously undetectable. To motivate this technique, we provide a problematic example. The following snippet of C code has a bug in it - the reader is implored to find it:

```c
#include <stdio.h>
#include <signal.h>
#include <unistd.h>

void sig_handler(int signo) {
    printf("Received signal %d\n", signo);
}

int main(void) {
    if (signal(SIGINT, sig_handler) == SIG_ERR) {
        printf("Could not register signal handler\n");
        return 1;
    }

    printf("Signal handler registered...\n");
    while (1) {
        printf("Waiting for signals...\n");
        sleep(1);
    }
}
```

Most well-seasoned C and C++ programmers would be at a loss to find the error - and the error certainly is obscure. A quotation from the glibc library reference may be helpful here:

> If a function uses a static variable or a global variable, or a dynamically-allocated object that it finds for itself, then it is non-reentrant and any two calls to the function can interfere.

By "two calls", the reference means two concurrent calls. In the above snippet of code, a SIGINT signal sent to the process preempts whatever function was currently executing and transfers execution to sig_handler. Sig_handler proceeds to call printf

which may or may not already be executing in the main context. This is problematic because printf grabs a global lock around stdout and in the case of concurrent calls results in deadlock. Not good.

The glibc library reference goes on to explicitly mention several common functions as being nonreentrant. A few of them are malloc, free, fprintf, printf, and any function that modifies the global errno, although any function which uses static, global, or dynamically-allocated state will fall into this category.

A stop-gap measure that could be implemented to solve this issue is to make a rule: *No interrupt handlers are allowed to call nonreentrant functions* and to ask your peers to inspect all code by hand to enforce this requirement. This is tedious, error-prone, and can be extremely difficuly for code at scale. Let's say, for instnace, that sig_handler called foo, and foo called bar, and bar called printf. Is it reasonable to expect a human to detect this error in judgement that occured through 4 layers of indirection? Probably not.

To solve this problem, and many others like it, we created a tool called funqual. Funqual allows C++ programmers to tag certain functions and will statically check the call-graph and function tags against a set of user-defined rules. This call-graph type system is totally orthogonal to the existing C++ type system and so does not interfere with or expand the existing type rules which should be familiar to C++ programmers. Instead, funqual provides an additional set of restrictions which, when used intelligently by the developer, can help to detect certain kinds of errors statically.

Funqual is written using libclang and does not require any additions to the syntax of C++. As such, funqual can be run on C++17 code "in the wild" (code not designed to work with funqual); additionally, code which has been annotated for use with funqual can be compiled directly with gcc or clang without any modification.

This thesis is laid out as follows: Chapter 2 covers background information and

formally develops the concepts of a call-graph and an indirect call. Chapter 3 covers related work in such a way as to contrast the techniques of funqual from the techniques used by other tools in this domain. Chapter 4 gets into the theoretical details of how the type system in funqual works including a high level overview, an in-depth explanation of each individual rule, and some formal arguments for correctness. Chapter 5 goes into the practical details about the implementation and usage of funqual. Chapter 6 demonstrates funqual in action by showing how to apply it in some real-world projects. Finally, Chapter 7 discusses future improvements that can be made to funqual and Chapter 8 offers a conclusion.

Chapter 2

BACKGROUND

This Chapter aims to provide context for funqual as well as to provide an intuition for why funqual works the way that it does. Section 2.1 presents a brief review of type systems that should be familiar to most programmers; special care is taken to define systems of type qualifiers. It is included to contrast with Section 2.2. Section 2.2 develops the concept of a call-graph and demonstrates how a type system might operate on it.

Type Qualifiers on Variables

In most research into type-systems, type qualifiers are a way to refine variable types in order to introduce additional constraints. These type qualifiers can generally be applied to any base type and can often be combined to form even more specific types. A classic example that most programmers of C-family languages will know is the `const` type qualifier. Any identifier with the `const` qualifier can be initialized with a value but can never be assigned to again. This restriction can be statically checked and can often help prevent certain types of errors when used intelligently by the programmer [3]. Another type qualifier which may be familiar to C programmers is `volatile` which tells the compiler (and programmer) that this variable may be changed suddenly by other execution environments [3]. The important thing to note is that the rules surrounding these type qualifiers are orthogonal to the rules of the main type system. A `const` identifier is treated the same way whether it a `const int` or a `const char*` or a `const Panda` or even a `const volatile int` - the *type* and the *type qualifiers* exist in separate type systems and so the rules are enforced separately.

Some compilers also have their own compiler-specific type qualifiers. In Microsoft Visual C++, function parameters that are modified by the caller and referenced by the callee can be annotated with the [Runtime::InteropServices::Out] qualifier to tell the programmer and the compiler that this is an out parameter. Having a programming environment rich in these type qualifiers can help make the intent of source code easier for the programmer to infer and make it possible for those intents to be statically checked by the compiler.

In the majority of these systems, defining additional type qualifiers is either relegated to the language designers or the compiler maintainers. There is not much tooling or support for the average programmer to create their own type qualifiers and there does not seem to be any sort of emphasis on creating project-specific qualifiers to help maintain program semantics.

Type Qualifiers on the Call Graph

The focus of this paper is on creating and analyzing type qualifiers for functions that constrain where those functions can and cannot be called. The central notion behind this sort of type checking is that every program has a call graph and that there are certain patterns in the call graph which must be prevented.

The call graph of a program is a directed graph where each function is a vertex and where each call is an edge directed from the caller to the callee. The type qualifiers in this context are applied to the vertices and the things we wish to constrain are connections between vertices. Below is an example of a C program and its associated call graph.

```c
int breed_and_release_pandas() {
    Panda *baby_panda = malloc(sizeof(Panda));
    release_panda(baby_panda);
}

int save_the_pandas() {
  stop_deforestation());
  if (pandas_are_saved()) {
    printf("Stopping deforestation saved the pandas!\n");
    return 1;
  }

  breed_and_release_pandas();
  if (pandas_are_saved()) {
    printf("Breeding pandas in captivation and releasing them has
     saved the pandas!\n");
    return 1;
  }

  return 0;
}

int main(void) {
  if (save_the_pandas()) {
    printf("The pandas have been saved!\n");
  }
}
```

Listing 2.1: Example C program. The call graph for this program is shown in Figure 2.1

As demonstrated in Figure 2.1, if there is a call from function X to function Y in the source code, there will be an edge pointing from node X to node Y in the associated call graph. We can say that main directly calls printf and save_the_pandas and that

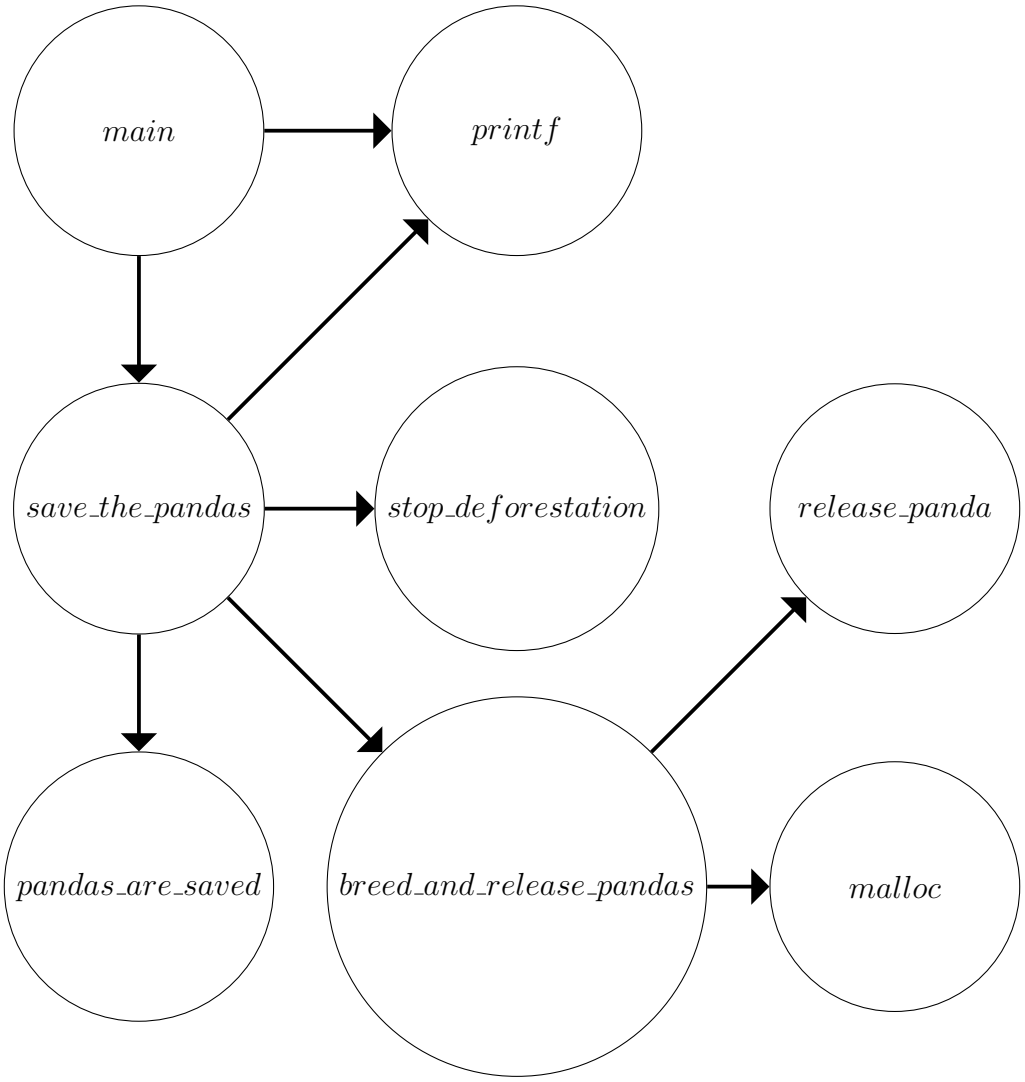

Figure 2.1: Example Call Graph. The source code associated with this call graph is showin in Listing 2.1

save_the_pandas directly calls pandas_are_saved, stop_deforestation, and breed_and_release_pandas because there is an edge in the graph that directly connects these functions. We can also say that main indirectly calls stop_deforestation because there is a path from main to stop_deforestation.

Let us now imagine that there is some constraint whereby save_the_pandas is not allowed to allocate memory. Using conventional tools, it would be possible to bar any function anywhere in the codebase from calling malloc or to simply link to a nonstandard library without malloc defined. This solution is problematic, however, because it prevents us from calling malloc anywhere in the codebase rather than just from save_the_pandas. What would be more useful is a system of marking functions that cannot call malloc and having a tool check the call graph to make sure it does not happen.

To accomplish this we will create two type qualifiers: static_memory and dynamic_memory. When the programmer qualifies a function with static_memory, that declares the intent that this function will *never* allocate memory on the heap. When the programmer qualifies a function with dynamic_memory, that declares the intent that this function always allocates memory on the heap. In the example about saving the pandas, we would tag save_the_pandas as static_memory and we would tag malloc as dynamic_memory. Below is the call diagram for the code again, but with static_memory functions marked green and with dynamic_memory functions marked red:

By turning the program into a directed graph and by assigning types to vertices, we have transformed the problem of type safety into a graph problem. A question like *are there any static_memory functions that inadvertently call dynamic_memory functions* essentially boils down to *are there any paths from green vertices to red vertices.* In this example, the answer to that question is yes. In the code, save_the_pandas calls breed_and_release_pandas which calls malloc constituting an illicit call. Equivalently,

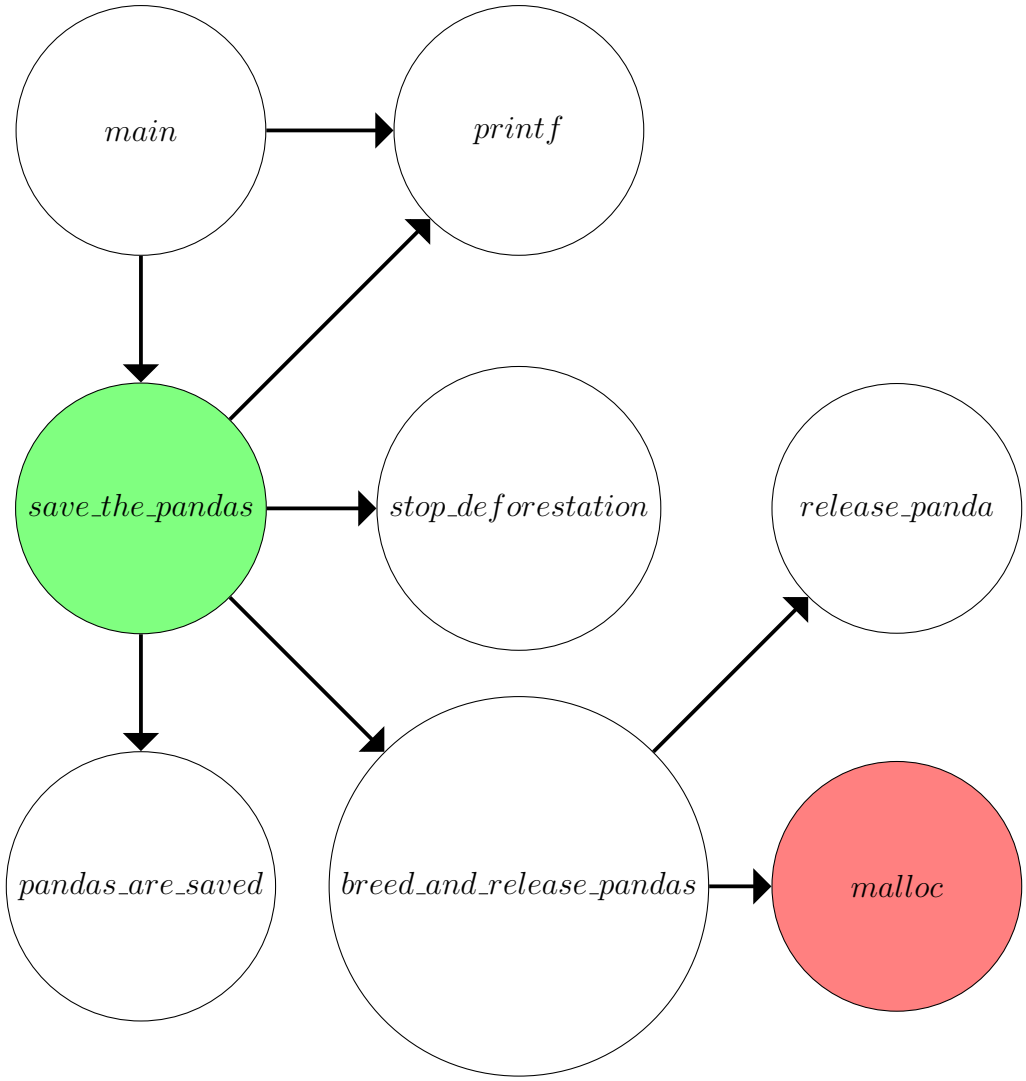

Figure 2.2: Color-coded Call Graph for Listing 2.1. Functions tagged `static_memory` **are highlighted green and functions tagged** `dynamic_memory` **are highlighted red.**

save_the_pandas has an edge to breed_and_release_pandas which has an edge to malloc constituting an illicit path. A well-typed program has no paths from green vertices to red vertices. A poorly-typed program will have at least one path.

This section only intends to establish the isomorphism between the program source and the call graph and to demonstrate the usefulness of this call graph representation. For a more detailed explanation of all the rules, refer to Chapter 4

Chapter 3

RELATED WORK

Static program analysis is a hot topic in Computer Science research. The Association for Computing Machinery publishes several journals that are focused (at least in part) on static verification and type systems. It should come as no surprise that there is a large body of research that is related to this thesis. This Chapter references a tiny subset of this body of work. Section 3.1 calls upon past research to assert unquestionably the positive impact that static analysis has on the software development process. Section 3.2 explores a line of research dedicated to inserting supplemental specifications into existing programming languages in order to improve the static checkability of those languages. Lastly, Section 3.3 pays respect to the LLVM project which has enabled so much of this research to happen.

On the Effectiveness of Static Analysis

Studies have long shown that Static Analysis is an essential tool for developing high-quality software. The high speed and low cost of this type of verification make it an economical method for finding faults in program code [14, 9].

Industry has taken this observation to heart. Many companies have their own internal tools dedicated to statically checking code changes with a goal of detecting common mistakes and stylistic issues. The Mozilla project is a good example of this - starting in the early 2000's, Mozilla has used fairly robust suite of internal tools specifically crafted for Mozillla's mostly C++ codebase. Using these tools, every Pull Request into Mozilla Firefox is parsed and checked against a set of hand-written rules to detect and report common issues [10, 4] [CAN I CITE JIRA TICKETS?]. Much of

this tooling was dedicated to detecting memory issues. Of course, without modifying the grammar of C++, there are limitations in what can be easily checked statically by these tools. Only a small subset of the problem could be effectively solved.

More recently, Mozilla has developed and began using another language called Rust which was designed with certain static analysis characteristics in mind. The Rust language implements an innovative type system meant to formally track the ownership of objects in memory. "Rust's type system and runtime guarantee the absence of data races, buffer overflows, stack overflows, and access to uninitialized or deallocated memory" [8]. A common sentiment in the Rust-language community is that even though the "Borrow Checker" (the part of the type system that enforces memory safety) seems complicated at first, seasoned Rust users learn to depend on it to help them reason through complicated programs [13]. Rust demonstrates that making a type system more expressive and more restrictive can improve both the static checkability of a programming language and also the help the users of those languages.

Aftermarket Type Systems - Supplementing an Existing Language

The idea of introducing new forms of type checking into an existing language to increase safety is nothing new. As early as 1994 tools such as LCLint have existed which allow the programmer to write down specifications about their code that are not necessarily supported by the original language standard. The LCLint tool can take program source code as well as a file containing supplemental specifications and perform static analysis that is more thorough and informed than could possibly be achieved through the language standard alone [2].

A useful attribute of these supplemental static analysis tools is that they scale incrementally - the programmer can use these tools to whatever extend they find

helpful and can increase or reduce the amount of information they pass on to these tools as they see fit. Since these specifications are opt-in, adding new forms of specification to a tool like LCLint is a straightforward way to expand the scope of the tool without breaking backwards compatibility. In 1996, a project added a few variable type annotations to LCLint such as not-null, possibly-null, and null which, when used by the programmer, allows LCLint to check for certain kinds of errors relating to nullness and memory allocation [1]. This modification requires zero action by the users who choose not to use it, but provides more and more feedback to users as they add more of these annotations.

In general, variable annotations like not-null and possibly-null are very similar in use to the existing system of type qualifiers in C family languages. A canonical example of a type qualifier would be the C const qualifier; a variable marked const may be set once at declaration but never updated again (ignoring unsafe casts). Type qualifiers and annotations like const and not-null restrict what the programmer can and cannot do with an identifier in the same way. These constructs explicitly declare the intent of the programmer and restrict what the programmer can do. However, their use is entirely optional - the programmer can choose to treat an identifier as const or not-null without actually codifying the intent [3].

"A Theory of Type Qualifiers" develops this concept in depth and explores the theoretical and practical concerns involved with using type qualifiers in a language [3]. One of the most relevant observations to this research is that every type qualifier introduces a form of subtyping. For all types T and any qualifier q, either $T \leq qT$ or $qT \leq T$ depending on q. Here we notate T qualified by q as qT and we notate X is a subtype of Y as $X \leq Y$. $X \leq Y$ should be interpreted to mean that X can be safely used whenever Y is expected. For example int $\leq$ const int because in any expression containing a const int, one could safely substitute an *int* however the reverse is not true. In the same vein, not-null char* $\leq$ char* because any expression referencing a

char* could safely be given a not-null char* instead [3]. In this paper we will apply this concept to the type qualifiers introduced by funqual in order to argue for the correctness of funqual.

libClang and the Explosion of C++ Tooling

C++ is difficult to parse [7, 12, 10, 11]. Years of language additions, the need for backwards compatibility, and the existence of a text-based preprocessor means that the language grammar is large and complicated. As a result, even the simplest static analysis tools require a huge amount of complexity to do basic parsing of source code. Up until relatively recently, many C++ language tools settled on doing a partial parse of the language using approximations and heuristics [12]. This method often leads to artificial constraints on the language or to incorrect interpretations of the source.

In the last few years, as a result of the LLVM Compiler Infrastructure Project, we now have an excellent set of tools for working with code. The Clang compiler is a fully featured compiler from the LLVM project that supports a wealth of C-family language standards including C++17. As a result of this project, we also have libClang which provides a convenient API to the parser and AST used by the Clang compiler. libClang enables developers to create their own tools that built on top of Clang's C++ parser. This means that developers of static analysis tools only need to focus on maintaining their project's contributions rather than supporting an entire parser/AST toolsuite [12]. Funqual is built using libClang and so the work done in this paper was only possible thanks to the work done by the LLVM Compiler Infrastructure Project.

Chapter 4

TYPE RULES

This chapter contains an overview of the rules implemented by funqual as well as a brief exploration of what needs to happen behind the scenes in order to correctly check these. The first section simply explains the process of marking functions. The second section shows what types of rules are supported by funqual. The third section demonstrates special considerations made for function pointers and explains the rules for their use. The final section explores the universe of special considerations and compromises made when creating the call-graph to be checked.

Note this section focuses only on the conceptual design of funqual. For any details on how to actually use it, refer to to 5.1.

Overview

Function Qualifier Annotations with QTAG

One of the goals of funqual was that it be entirely compatible with the C++17 standard. As such, funqual does not add any syntaxes to the language that would prevent annotated programs from being used by other tools (such as gcc or cppchecker). Additionally, any C++17 code that exists "in the wild" should be checkable by funqual with no modification. To this end, we use the existing C++17 annotation syntax to mark code.

For clarity and convenience we assume the following macro is in scope. In practice, this macro can be repeated in the codebase or included in files containing function annotations:

```
#ifndef QTAG
#define QTAG(TAG) __attribute__((annotate("funqual::" #TAG)))
#endif
```

Note that the __attribute__((annotate(foobar))) syntax is generally used for compiler-specific directives (like packed, allign(8), noreturn, etc) and that attributes unknown by the compiler are simply ignored. This allows us to insert information into the AST that is available after parsing but which will not effect compilation.

Below is an example of the syntax for adding type qualifiers to a function. The function below has two qualified types: static_memory and no_io.

```
int main() QTAG(static_memory) QTAG(no_io) {
    return 0;
}
```

Below is an example of the syntax for adding type qualifiers to a method prototype inline a class. The function below has qualified type static_memory.

```
class Panda {
    Panda() QTAG(static_memory);
};
```

Below is an example of the syntax for adding a type qualifier to a function pointer. The function pointer below has qualified type static_memory.

```
int QTAG(static_memory) (*func)(int, int);
```

Functions in the standard library can be annotated by simply repeating their prototype and adding a type qualifier annotation. During the first phase of type checking, funqual will scrape the entire codebase and determine the union of all type annotations for each function symbol. The following are a few examples:

```
void *malloc(size_t size) QTAG(dynamic_memory);
```

```
2
3 // multiple qualifiers can be added at once like so
4 int printf(const char *__restrict __format, ...) QTAG(io) QTAG(blocking)
    ;
5
6 // the same function can be annotated in multiple places like so
7 // funqual will enforce the union
8 void *malloc(size_t size) QTAG(blocking);
```

Basic Rules

Restrict Direct Call

$$restrict\_direct(X, Y) = (V \in X \implies Y \notin A) \mid (V, A) \in G$$

A restrict direct call requires that functions in set X only ever call functions in set Y. This constraint can be checked in time that is linear with the number of function calls in the program and can be reported very easily. An example use case for this type of restriction might be to restrict realtime functions to only calling other realtime functions.

Restrict Indirect Call

$$restrict\_indirect(X, Y) =$$

Require Direct Call

$$require\_direct(X, Y) = (V \in X \implies Y \in A) \mid (V, A) \in G$$

A require direct call requires that functions in set X never call functions in set Y.

Function Pointers Pointing

Basic Annotation and Direct Type with QTAG

Indirect Type with QTAG_IND

Rules of Assignment

Special Considerations when Creating a Call Graph

Bridging the Divide between Translation Units

The compilation of C++ code is driven by translation units. Translation units are the files which are inputted into the C compiler to be translated into object files. In general, translation units are singular *.c* or *.cpp* files where the preprocessor has already expanded all macros (including *include* substitutions). During this process, many symbols are said to have *externallinkage* meaning that their type is specified in this translation unit but not their value or definition (this is the case with extern variables, function prototypes, and class forward declarations). In these cases, examining the call tree of a single translation unit is not sufficient to enforcing global call-tree constraints because we would be able to see which internally linked functions call externally linked functions but not vise versa.

To solve this problem we need to examine every translation unit in the source tree and build a call tree which represents the entire codebase. In order to test this, we create several test cases where functions are defined in multiple translation units and where function a call tree constraint is violated between translation units.

Dealing with Inheritance

According to the Liskov Substution Principal, "if S is a subtype of T, then objects of type T in a program may be replaced with objects of type S without altering any of the desirable properties of that program". In this work, we assume this to be a basic principal of object oriented design and build off it. For the purpose of this paper, "if S is a subtype of T and M is a method of S, then calls to $T.M$ in a program may be replaced with objects of $S.M$ without altering any of the desirable properties of that program". As a result of this, when typechecking a call to $T.M$, we must also typecheck a call to $S.M$ to ensure that substituting S for M does not violate our call tree constraints.

In practice, this mean that for any method call from C to $T.M$ where C is the calling context and M is a method of T, we must add an edge in our call graph from C to $T.M$ and also from C to $S.M$ for any S that is a direct or indirect subtype of T.

Below is a code example that demonstrates this rule in use:

```
1  void *malloc(size_t size) FUNQUAL(dynamic_memory);
2
3  class Panda {
4  protected:
5      int m_hunger;
6  public:
7      int Feed() {
8          m_hunger--;
9      }
10 };
11
12 class RedPanda : public Panda{
13 public:
14     int Feed() {
15         char *buff = malloc(30);
16         m_hunger--;
17     }
18 };
19
20 void feedPanda(Panda *panda) FUNQUAL(static_memory) {
21     panda->Feed();
22 }
23
24 int main(void) {
25     feedPanda(new RedPanda());
26 }
```

This example shows a function called feedPanda which calls $Panda.Feed$. This function also shows that *malloc* is tagged with *dynamic_memory* and that $feedPanda$ is tagged with *static_memory*. Presumably there is a indirect call restriction that prevents functions tagged with static_memory from calling (either directly or indirectly) functions tagged with dynamic_memory. It we simply looked at the type of *panda*, we

would falsely believe that this program is typesafe. However, we see that it's possible for the actual type of *panda* to be $RedPanda$ in which case we call $RedPanda :: Feed$ which calls *malloc* which violates our static memory constraint. To solve this problem, we must create a call graph which contains edges pointing to both $Panda :: Feed$ and $RedPanda :: Feed$.

Function Pointers Pointing

Just like functions, function pointers need to have their place in the call graph. Function pointers are difficult because we can't always know at build-time what they refer to. With a standard function, we can simply build a mapping that goes from the function to its body. With function pointers, we have to be able to accommodate for the pointer referencing different functions at different times.

To solve this problem, we allude to the existing type system on function pointers. According to the C++ standard, in order to assign a function pointer to reference an existing function, the type of the function pointer must match the type of the function being referenced. We continue this trend by forcing the type qualifiers of the function pointer to match the type qualifiers of the function being referenced. These type qualifiers can, of course, be forcibly removed by a cast in extreme circumstances, but we believe that this rule ensure consistency between within the call tree in the face of function pointers.

Checking the Call Graph

This section contains explanation and motivation behind the call graph rules implemented in this tool.

Chapter 5

IMPLEMENTATION

Operation

Chapter 6

APPLICATION

Glibc Nonreentrant Functions

The following functions are documented in glibc to be non-reentrant:

1. malloc
2. free
3. printf

There are others. We can mark interrupt handlers as one class and these functions as another and statially check that.

Restricting API available during initialization

My OS project was annotated so I didn't accidentally call malloc or printf before those things were initialized

Detecting noisy calls in high frequency contexts

Robotics was annotated and checked so I didn't accidentally have printf's in high frequency functions.

Chapter 7

FUTURE WORK

The following things are not handled correctly by the tool but it would be cool if they were:

1. struct fields
2. casting of function types
3. arrays of function pointers

future work should implement these features.

Chapter 8

CONCLUSION

It worked good. How do I measure that though?

BIBLIOGRAPHY

[1] D. Evans. Static detection of dynamic memory errors. *SIGPLAN*, May 1996.

[2] D. Evans, J. Guttag, J. Horning, and Y. M. Tan. Lclint: A tool for using specifications to check code. *SIGSOFT Symposium on the Foundations of Software Engineering*, December 1994.

[3] J. Foster, M. Faehnlich, and A. Aiken. A theory of type qualifiers. May 1999.

[4] T. Glek. Dehydra, prcheck, squash in mercurial, July 2007.

[5] D. Greenfieldboyce and J. Foster. Type qualifiers for java. August 2005.

[6] D. Greenfieldboyce and J. Foster. Type qualifier inference for java. 2007.

[7] Y. Kreinin. Defective c++, November 2016.

[8] N. Matsakis and F. S. K. II. The rust language. *ACM SIGAda*, October 2014.

[9] H. Ogasawara, M. Aizawa, and A. Yamada. Experiences with program static analysis. 1998.

[10] V. Ordy. Writing and designing c++ extensions and transformers. December 2009.

[11] Y. Padioleau. Parsing c/c++ code without pre-processing. In *Proceedings of the 18th International Conference on Compiler Construction: Held As Part of the Joint European Conferences on Theory and Practice of Software, ETAPS 2009*, CC '09, pages 109–125, Berlin, Heidelberg, 2009. Springer-Verlag.

[12] S. Schaub and B. A. Malloy. Comprehensive analysis of c++ applications using libclang api. October 2014.

[13] T. R. Team. The rust programming language. May 2015.

[14] J. Zheng, L. Williams, N. Nagappan, W. Snipes, J. P. Hudepohl, and M. A. Vouk. On the value of static analysis for fault detection in software. *IEEE Transactions in Software Engineering*, 32.