Vrije Universiteit Amsterdam


Bachelor Thesis

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# Sample Title

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**Abstract**

Abstract goes here.

# 1 Introduction

The introduction should cover

- why reliability is important
- specifically in filesystems - why do you need a reliable filesystem?
- what's done in this paper (high-level summary)

# 2 Background information

## 2.1 C as the implementation language

The choice of an implementation language may affect the bugs or vulnerabilities that are present in the system. The de-facto standard implementation language for operating systems and their components has long been C. Many popular file systems are implemented in C, such as Ext4 [1]. C is based on typeless languages, BCPL and B, which were developed specifically for operating system programming in early Unix. A design principle of C was to be grounded in the operations and data types provided by the computer, while offering abstractions and portability to the programmer [2]. Due to its history, and because C compilers exist for essentially any processor, C is the natural choice for systems programming.

However, many of the characteristics that make C flexible and versatile also place more responsibility on the programmer to ensure that the resulting code is bug-free. The permissiveness of C means that, especially in a large codebase, bugs are hard to avoid and often even harder to troubleshoot. In the worst case, errors in the code allowing null pointer dereferences or buffer overflows can lead to serious security vulnerabilities affecting thousands of devices [3]. In 2017, Ray et al. analyzed 850 projects across 17 different programming languages, and found that those with unmanaged memory, such as C, introduce more memory errors [4]. Furthermore, C introdced 19.15% of concurrency errors. Another study conducted by WhiteSource found that C has the highest vulnerabilities out of all seven analyzed languages, with 50% of all reported vulnerabilities in ten years [5]. Of course, it is important to note that this is in part because more code has been written in C than in any other language, and because C has been in use for much longer than most other languages. WhiteSource note that buffer errors, with the Common Weakness Enumeration (CWE) number CWE-119, are by far the most common security vulnerability in C code.

Specifically in filesystems, a study of 157 cases reported to the Common Vulnerabilities and Exposures (CVE) database between the years 1999 and 2019 was conducted, covering a variety of filesystems including Ext4 and XFS [6]. Cai et al. found that errors that cause denial of service account for 75% of all vulnerabilities. They concluded that the four largest causes of denial of service are kernel crashes (35% of vulnerabilities), memory corruption (16% of vulnerabilities), memory consumption (13%), and system hang (9%). Kernel crashes and memory corruption can be caused by exploiting invalid pointer dereferences or out-of-bounds memory access, and memory consumption is caused by not properly freeing allocated objects.

In summary, although C is the 'traditional' systems programming language, code written in C can be error prone and lead to issues, unless the programmer is aware of the issues and takes explicit steps to prevent them. Even a simple "Hello World" program exposes some of the most dangerous features of the language [7]. Therefore, it would be beneficial to find a better method, a way to write more reliable systems with less burden resting on the programmer.

## 2.2 Possible alternatives to C

Given the issues with C code, what alternatives are there? It is possible to subset C and allow only statements or expressions considered suitable for reliable software, or perhaps instead of retroactively imposing restrictions on a language, it would be more beneficial to use a language designed with safety properties in mind.

**Restricting C** One option is to use a restricted version of C. MISRA C is a coding standard which was initially aimed at the automotive sector (with MISRA standing for the Motor Industry Software Reliability Association), but which later spread to other sectors that require safety and security in C code [8]. Originally supported by the UK government, the goal of the MISRA project was to develop best practice guidelines for reliable software, and the guidelines also deeply influenced NASA's coding standards. These guidelines prescribe restricting a "standardized structured language" to a subset of its operations, banning non-definitie behavior and constraining implementation-defined behavior and compiler extensions. They come in the form of directives (specifications for information that is not fully contained in the code, such as requirements or design) and rules (specifications for code). Every guideline is in one of three categories: mandatory (the code must comply with the guideline), required (the code shall comply with the guideline, and a formal deviation description is required if this is not the case), and advisory (the code should comply with the guideline; formal description of a deviation is not required, but the deviation should be documented). If a piece of C code follows these guidelines, it is easier to verify that safety and security properties hold.

Another approach is Frama-C, a collection of plugins that perform a series of checks (static analysis, deductive verification, testing) on C programs [9]. Frama-C uses the ACSL formal specification language, and extends CIL (a C front-end that normalises ISO C99 programs such that loop constructs have a single form, expressions are free from side-effects, etc.) to support ACSL annotations in the source code. The annotations describe the functional properties of C programs, stating the pre-conditions a function requires from its caller and the post-conditions it ensures when returning. There is also a clause to specify which memory locations are assigned by the function. Furthermore, it is possible to insert annotations directly into the code, as assertions.

**The D language** D is a multi-paradigm language for systems programming that is compatible with the C application binary interface, and has a direct interface to the operating system APIs and hardware [10]. It is statically typed, and allows programming with contracts. Specifically, programmers can define assertions, and pre- and post-conditions, which take the form of boolean expressions or blocks of arbitrary code [11]. D also allows the definition of invariants – properties of classes or structs that must always be true [11]. It is possible to use the *pure* keyword to ensure that a function does not access (read or write) any global mutable state, and to preserve referential transparency, function parameters can be marked as immutable [12]. Moreover, D has a memory-safe subset, called SafeD, which also removes undefined behavior. The design team expects the majority of programmers to operate within SafeD [7].

**Rust** Rust is a relatively new project that attempts to compete with languages such as C as C++ in the systems development space, while putting the largest emphasis on safety [13]. It ensures static safety by forbidding wild and null pointers, and functions are pure by default. All errors cause failure, and task failures are non-recoverable. The static rules can be broken in code, but only if this is explicitly authorised in the code. There is no shared mutable state, and the language has strict ownership rules where each value has exactly one owner at any time [14]. Rust has already been used for several large projects, including the Stratis storage management

system[1] and the Redox microkernel operating system[2].

**Coq** Coq is an interactive theorem prover for development of mathematical proofs, and for verification of programs with respect to their formal specifications [15]. Specifications are written in the Gallina language, whose terms can represent programs, properties of the programs, and proofs of the properties. All three of these are formalised in the Calculus of Inductive Constructions, which is a lambda-calculus with a rich type system. Coq can be used to build certified programs that are relatively efficient, and programs can be extracted in the functional languages OCaml, Haskell, and Scheme. Program extraction is conducted via a constructive proof of its specification. For example, the CompCert compiler[3] for almost the entirety of the C language is largely programmed and proved using Coq.

**Ada** Finally, write here about Ada.

### 2.3 Formal verification

Explain what it is, particularly Hoare triples. Why is it useful?

### 2.4 FUSE

Why use it for development, what are its limitations?

## 3 Related work

In this section we summarise the existing body of work relating to formal verification of filesystems.

### 3.1 Flashix

In 2014, Schellhorn et al. presented their work on a verified Flash filesystem [16]. Since Flash memory can only be written sequentially, and data in Flash memory cannot be overwritten in place (i.e. space can only be reused by erasing entire blocks), a special Flash file system must be used that is designed to work with Flah memory. Flashix, the verified Flash filesystem they developed, is based on UBIFS. They refined the high-level POSIX system interface using a Virtual Filesystem Switch (VFS) that maps POSIX operations to one or more Abstract File System (AFS) operations; the AFS is a model that captures the functional behavior of a specific filesystem [17]. The reason for this separation is that specific filesystems do not implement generic functionality, but instead satisfy an internal interface. To provide safety for crashes, power cuts, and other such events, they used a transactional journal providing atomic writes [18]. They verifed the code using the KIV interactive theorem prover, whose specification language is based on Abstract State Machines and Abstract State Machine refinement. They then used tools to generate a Scala implementation, which could be mounted using the FUSE library and executed on the Java Virtual Machine.

### 3.2 COGENT

COGENT is a new, restricted language developed by Amani et al. [19], as an approach to writing and formally verifying high-assurance filesystem code. It was designed to bridge the gap between

[1] `https://stratis-storage.github.io/`

[2] `https://www.redox-os.org/`

[3] `http://compcert.inria.fr/compcert-C.html`

the formal specification of a program and its low-level implementation, and to allow programmers that do not have a background in formal verification to provably avoid common errors. Many of the characteristics required to guarantee the absence of common filesystem implementation errors were encoded in the language, which is strongly typed, type safe, and uses a linear type system (meaning that every variable must be used exactly once). The compiler for the language generates C code and translation correctness proofs, enforces memory safety, and forbids undefined behavior in C code (such as null pointer dereferences or buffer overflows). In evaluation, they found that code generated from COGENT has throughput that is almost identical to a C implementation, albeit with slightly increased CPU usage. The disadvantage is that programmers were required to learn a new language (which has a functional style and whose type system is less common) solely for the development of a filesystem, though the authors state that these were not major barriers.

## 3.3 Recon

Fryer et al. found that filesystem bugs that severly corrupt metadata are common, and that solutions to the necessary recovery procedures were unsatisfactory. Therefore, they developed Recon, a system to protect filesystem metadata from arbitrary implementation bugs [20]. Recon sits between the filesystem and the block layer, and checks consistency invariants at commit points before allowing writes to disk. Thus, failures that would be silent become detectable violations of these invariants. Consistency invariants are declarative statements that must be satisfied before data is committed to disk, otherwise the filesystem may become corrupted. The authors use the consistency rules used by a file system checker (*e2fsck* in their implementation) to derive the invariants. Consequently, the system can detect random corruption at runtime as effectively as a filesystem checker. In essence, Recon can conduct online checks similar to those conducted by offline filesystem checkers (e.g. *fsck*).

## 3.4 FSCQ & DFSCQ

FSCQ was the first file system that has a machine-checkable proof (as opposed to an interactive proof) that its specification and implementation match, and whose specification included crashes [21]. Chen et al. found that to achieve their design goals of atomic system calls, preventing real bugs, enabling proof automation, and allowing modularity, an extended variant of Hoare logic worked best. Accordingly, they developed Crash Hoare logic, which allows programmers to write a specification of the behavior of a storage system in the face of a crash, and to prove them correct (i.e. if a computer crashes, the storage system will reboot into a state consistent with its specification). This extension of Hoare logic takes into account the fact that during a crash, a procedure may stop at any point, and that recovery procedures may run. The filesystem uses FscqLog, a write-ahead log also certified with Crash Hoare logic, which provides atomic transactions on top of asynchronous disk writes. FSCQ was developed with the same features as the educational xv6 filesystem, which implements the Unix v6 filesystem with write-ahead logging. The implementation used the Coq proof assistant, and generated Haskell code, which could be mounted with the FUSE library and a Haskell driver. Based on FSCQ, DFSCQ (Deferred-write FSCQ) was later written to provide a precise specification for *fsync* and *fdatasync* in the case of log-bypass writes [22]. Deferring writing data to persistent storage allow filesystem to achieve high I/O performance, and DFSCQ's implementation would provide crash safety for these operations. In building DFSCQ, the authors presented a tree-based approach to specifying filesystem behavior, and a metadata-prefix specification to specify behavior for crashes. Compared to FSCQ, DFSCQ has several optimisations and provides a number of missing features.

### 3.5 Yggdrasil & Yxv6

In 2016, Sigurbjarnarson et al. presented Yggdrasil, a toolkit which uses a push-button approach to formal verification [23]. Yggdrasil does not require manual annotations or proofs, and aids programmers by producing counterexamples for failed verification constraints. To achieve this, the authors used *crash refinement*, i.e. that the set of all disk states reachable in the implementation must be a subset of those allowed in the specification. Push-button verification means that Yggdrasil asks the programmer to enter the specification of the expected behavior, the implementation, and any consistency invariants for the state of the filesystem image, and it then checks if the implementation meets the specification while satisfying the invariants. All three inputs are written in the same language (a subset of Python), and Yggdrasil generates C code, which is compiled to an executable filesystem and can be mounted using the FUSE library. The authors used Yggdrasil to implement a journaling filesystem, Yxv6, which is similar to xv6 and FSCQ, as well as a file copy utility (Ycp) and a persistent log (Ylog).

### 3.6 Argosy

Argosy is a framework to allow machine-checked verification of storage systems, and introduces recovery refinement, which is a set of conditions that guarantee that an implementation of an interface with a recovery procedure is correct [24]. Recovery refinement ensures correctness for anything using the specification, and can compose with other refinements to prove that an entire system is correct. Its semantics are formulated in Kleene algebra. The system implements Crash Hoare logic, which was introduced by and used in FSCQ, to prove recovery refinement. Therefore, the authors produce a verified transactional disk API for unreliable disks. Similarly to FSCQ, the code is verified using the Coq proof assistant, and produces Haskell code.

## 4 Design & implementation

To explore ways of writing reliable code, a small, prototype filesystem (AdaFS) was implemented using the Ada 2012 programming language. Some parts of this filesystem are written in the SPARK 2014 language, which is a subset of Ada that removes features not amenable to formal verification, and defines new aspects to support modular, constructive, formal verification [25]. The AdaCore GNAT Community 2020 package[4] is used, which provides, among others, the compiler and prover tools. For testing purposes, a FUSE driver is written in C, and the built executables are linked with libfuse 3.9.2[5]. The GNAT Project Manager is used to facilitate compilation of source files in different languages and linking of other required libraries.

### 4.1 Filesystem design

AdaFS is based on the MINIX 2 filesystem [26], with some simplifications due to time constraints. The MINIX operating system was written by Andrew Tanenbaum as an educational tool, and is compatible with UNIX, but has a more modular structure. The MINIX filesystem was chosen as a model because it is not part of the operating system, but rather runs entirely as a user program. As such, it is self-contained. Furthermore, due to its educational purpose, it is thoroughly commented and easy to understand. The second version of the file system was chosen because MINIX 3 is more complex, as it adds numerous improvements (e.g. for reliability) to place emphasis on its use in research and production [27].

A disk is formatted as an AdaFS filesystem using the *mkfs* executable. The resulting disk layout is shown in Figure 1. The disk is divided into blocks of 1024 bytes, similarly to MINIX.

[4] `https://www.adacore.com/community`

[5] `https://github.com/libfuse/libfuse`

Blocks are collected in zones, which can be of size $2^n$ blocks. This abstraction of blocks into zones can make it possible to allocate multiple blocks at once.

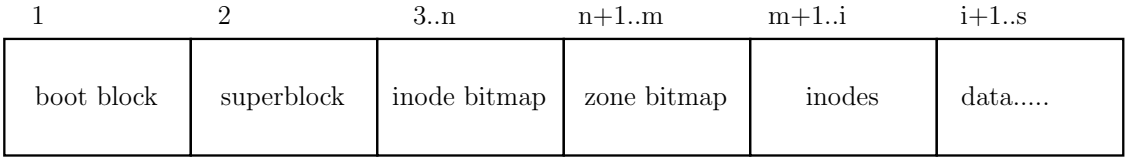



*Figure 1: AdaFS disk layout. (n = number of inode bitmap blocks, m = number of zone bitmap blocks, i = number of inode blocks, s = number of blocks on disk)*

The disk begins with a boot block that would optionally contain executable code. Then, it contains a superblock, and two bitmaps. The bitmaps are used for inode and zone allocation, and can potentially span multiple blocks. Next, there are a few blocks containing space for inodes, potentially with more than one inode per block. Finally, the rest of the blocks contain user data.

The superblock is the second block on the disk, and contains information about the layout of the filesystem. In particular, it contains the number of inodes and zones on disk, the number of inode and zone bitmap blocks, the number of the first data zone, the base-2 logarithm of the number of blocks per zone, the maximum file size, and the magic number. The magic number used to identify a correctly formatted disk is $\text{CACA}_{16}$; MINIX uses the magic number $2468_{16}$, but AdaFS avoids using the same number because a disk formatted by the AdaFS *mkfs* utility is not necessarily equivalent to a disk formatted by the MINIX *mkfs* utility.

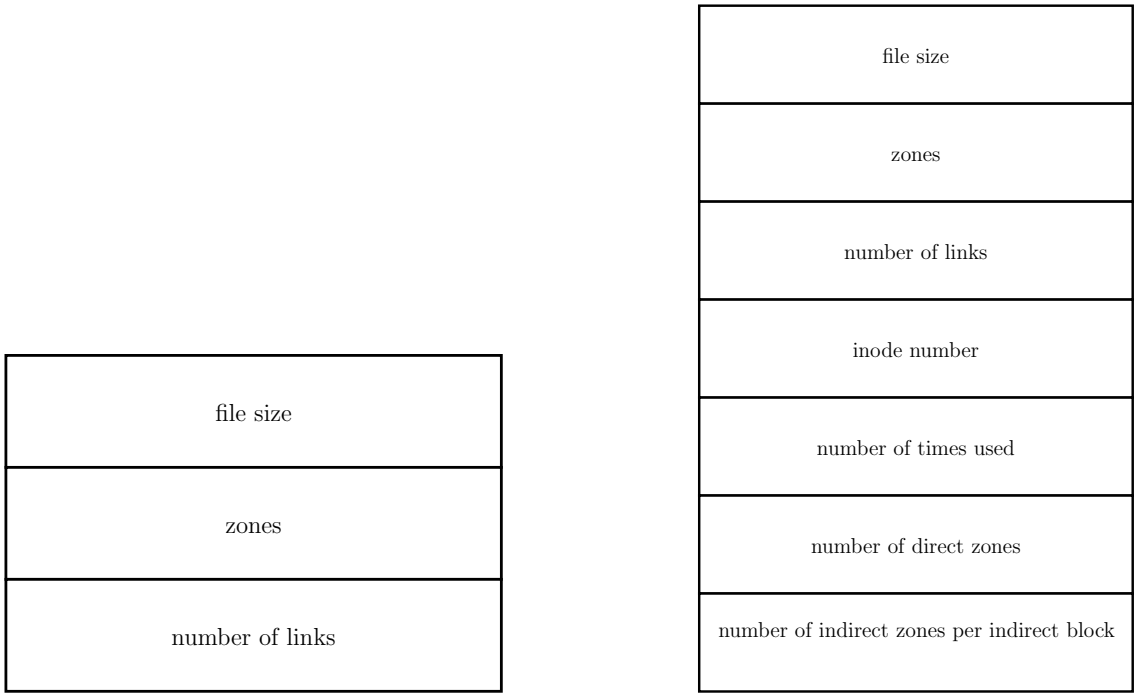
The two bitmaps keep track of available inodes and zones, where the $n$th bit of the inode or zone bitmap corresponds to the $n$th inode or zone on disk, respectively. If a bit in the inode bitmap is set to 1, that means the corresponding inode is allocated, and if it is set to 0, the inode is free. This is the same for the zone bitmap, pertaining to zones. One difference with MINIX is that, in MINIX, the first bit (bit zero) in the bitmaps must always be allocated, as the procedure that searches for a free inode or zone returns zero if no free inode/zone is found. In Ada, indexing generally starts at 1, so all bits can be used – as the first bit is bit one, this does not interfere with the allocation procedure.

The penultimate section of the disk contains inodes; the number of inodes is determined by the size of the disk. The inodes have two representations: on-disk (Figure 2a) and in-memory (Figure 2b). This allows the filesystem to make efficient use of disk space, while providing faster access to important values when the inode is loaded in memory. There are 10 zones per inode: 7 direct zones (those that contain data), 1 single indirect zone (indicates a block that contains more direct zones), 1 double indirect zone (indicates a block that contains more single indirect zones), and 1 unused zone. The unused zone is present for future use, potentially as a triple-indirect zone.

The final section spans the rest of the blocks on the disk, broken into zones, and is available to store user data. It can contain file data, or directory entries.

There are also some in-memory structures for working with open files. The filesystem keeps a process table in memory, which is indexed by process ID (PID), and keeps track of inode information for all processes using the filesystem. One entry corresponds to one process, and contains the inode numbers for the root and working directories of the process, as well as the list of open file descriptors. Each open file descriptor corresponds to an entry in the filesystem's *filp* table, which is shared among all processes and contains all the file position. The rationale for a shared file position table comes from MINIX, and is based on problems with the semantics of the *fork* system call [26]. An entry in the filp table contains the number of file descriptors using that entry, the inode number, and the file position for the inode.

Due to time constraints, a number of simplifications were made compared to MINIX. In particular, only the features necessary for basic functionality of the system were implemented.




*(a) On disk* *(b) In memory*

*Figure 2: Inode representations*

The filesystem does not cache any information, and there is no in-memory inode table; all data is written directly to disk. Furthermore, the current implementation does not keep track of file mode, owner, group, or timestamps. This results in a limited filesystem, which nonetheless completes its function as a proof-of-concept.

## 4.2 Language features & implementation specifics

**Strong typing** Ada is a strongly typed language, which helps the programmer distinguish between types that are logically different, even if their underlying representation is the same. Furthermore, the compiler will automatically catch any bugs that would be caused by assigning a value of an incorrect type to a variable. In order for a value to be assigned to a variable, two constraints must be satisfied: the value and variable must have the same type, and the value must satisfy all constraints on the variable (such as the range for an integral data type) [28]. Conversion between types is allowed, but only if it is explicit, and if the target type is an ancestor of the current type (for example, a positive integer may be converted to an integer, but not vice-versa). An example of the use of types is the definition of a character buffer of arbitrary size, followed by the definitions of different block types including a constrained version of the buffer type, shown in Listing 1.

```
type data_buf_t is array (Positive range <>) of Character;

type inode_block_t is array (1..block_size/on_disk'Size) of on_disk;
type zone_block_t is array (1..n_indirects_in_block) of Natural;
type dir_entry_block_t is array (1..block_size/direct'Size) of direct;
subtype data_block_t is data_buf_t (1..data_block_range'Last);
```

*Listing 1: Block type definitions*

**Controlled types** Controlled types allow the programmer to specify precisely what happens when a variable of a given type is declared, or when it goes out of scope. They are not permitted in SPARK, because the compiler inserts implicit calls to allow this functionality [25]. The initialization and destruction of variables of a controlled type is handled with custom `initialize` and `finalize` procedures for the type, thus the compiler needs to ensure these procedures are called in execution. However, in AdaFS, controlled types are not used for any filesystem logic, and are only used with disk I/O to make sure that e.g. the variable containing the superblock is initialized properly with the type of I/O the filesystem uses. Therefore, this was deemed acceptable for this prototype.

**Lack of pointers** The C codebase of MINIX makes extensive use of pointers to refer to inodes and other structures in memory, addresses on disk, etc. Ada has access types, which are similar to pointers in some ways, but due to the complexity of verifying a program's behavior when it contains pointers, SPARK severly restricts the possibilities of using access types [25]. Thus, alternative methods must be used to provide similar functionality.

One way to solve this is with parameter modes. Ada allows specifying the mode of each parameter in a procedure, which designates how the parameter will be used in execution. If a parameter is of 'in' mode, it is only read in the procedure, and is not modified – this is the default mode. If a parameter is of 'out' mode, the value of the parameter before the call is irrelevant, as it will receive a value in the procedure. Finally, if a parameter is of 'in out' mode, it is both read and updated in the procedure. This third mode provides functionality similar to a pointer.

However, SPARK requires that functions be purely functional; that is, they cannot have side effects, such as parameters with a mode of 'out' or 'in out'. Here, two solutions are possible. In some cases, it may be preferred to add the return value as an 'out' parameter, and rewrite the function as a procedure. In other cases, it is better for the function to return multiple values, which is possible with a record type. An example is the function `parse_next` in Listing 2, which returns two values, wrapped in the record type `parsed_res_t`.

```
subtype cursor_t is Natural range path'Range;

type parsed_res_t is record
   next : adafs.name_t;
   new_cursor : cursor_t;
end record;

function parse_next
   (path : adafs.path_t; cursor : cursor_t) return parsed_res_t
is
   ...
end parse_next;
```

*Listing 2: Parse function returning the parsed component and the new cursor position (ellipses denote code omitted for brevity)*

**Modularisation** Ada supports modularisation in the form of packages, and forms a single translation unit, which can contain member entities such as subprograms, variables, and types. Information hiding is done by defining members as private. A package is separated into two parts, which are placed in separate files: the *specification* (the public interface for the package), and the *body* (the implementation). The compiler always checks whether the package body matches the specification, and refuses to compile the code if this is not the case. Listing 3 shows an excerpt of the specification and body of the `adafs.inode` package.

A package can also have child packages: for example, the adafs.inode package is a child of the adafs package. A child package has access to all member entities defined in the specification of its parent(s), including private members.

```
-- adafs-inode.ads
package adafs.inode
  with SPARK_Mode
is
  ...
  function calc_num_inodes_for_blocks (nblocks : Natural) return Natural
    with ...;
end package adafs.inode

-- adafs-inode.adb
package body adafs.inode
  with SPARK_Mode
is
  function calc_num_inodes_for_blocks
    (nblocks : Natural) return Natural
  is
    inode_max : constant := 65535;
    i : Natural := nblocks/3;
  begin
    ...
    return i;
  end calc_num_inodes_for_blocks;
end adafs.inode;
```

*Listing 3: Excerpt from the adafs.inode package specification and body (ellipses denote code omitted for brevity)*

It is also possible to create *generics*. Generics are somewhat similar to objects in the OOP paradigm, in that they can be instantiated with parameters. However, an important difference is that instantiation can only occur in a declarative region. Both subprograms and packages can be generic. For example, Listing 4 shows a generic function for reading data from a disk, and its instantiation. As Ada's Stream_IO requires specifying the type to be read, using a generic function helps with code reuse, with elem_t designating the type to be read, which is passed in at instantiation. The downside of generics is that they cannot be analyzed directly by SPARK, but must instead be verified from the context of instantiation (i.e., SPARK mode must be enabled in the package or subprogram that instantiates the generic) [25].

```
-- disk.ads
generic
  type elem_t is private;
function read_block (num : block_num) return elem_t;

-- disk.adb
function read_block (num : block_num) return elem_t is
  result : elem_t;
begin
  if not is_reading then
    sio.set_mode(stream_io_disk_ft, sio.in_file);
  end if;
```

```
   go_block (num);
   elem_t'read (stream_io_disk_acc, result);
   return result;
end read_block;
```

*Listing 4: Generic function for reading a block of type* elem_t

**Interfacing with other languages** Ada has a mechanism to allow interfacing with other programming languages, such as Fortran, COBOL, or C. This is done by replicating the types and subprogram signatures in Ada. The Interfaces library package[6] provides types and subprograms for this purpose. For example, for C, there are the Interfaces.C[7] and Interfaces.C.Strings[8] packages, which provide the types chars_ptr (mirroring **char**∗ in C), int (mirroring **int** in C), etc. This allows *exporting* subprograms from Ada, and calling them from a C program. Listing 5 shows a specification of a subprogram that is exported to C by specifying the Export and Convention aspects (as well as an external name to use when calling the subprogram from C). The subprogram is then declared as **extern** in C, and called from the C program's main function. Since the main program is written in a language different from Ada, the initialization and finalization procedures (adainit(**void**) and adafinal(**void**)) must also be declared and called before and after any other Ada subprograms, respectively. The GNAT Project Manager handles compiling and linking of files written in different languages. Unfortunately, interfacing code is not amenable to formal verification.

```
-- declarations.ads
with Interfaces.C;
package Declarations is
   function Factorial (n : Interfaces.C.int) return Interfaces.C.int
      with Export => True,
           Convention => C,
           External_Name => "ada_factorial";
end Declarations;

-- main.c
#include <stdio.h>
extern void adainit (void);
extern void adafinal (void);
extern int ada_factorial(int n);

int main(int argc, const char *argv[]) {
   adainit();
   int n = 5;
   printf("%d\n", ada_factorial(n)); // 120
   adafinal();
}
```

*Listing 5: Interfacing code written in C and Ada.* declarations.adb *is omitted for brevity, but is assumed to contain an implementation of the factorial function conforming to the specification.*

[6] https://www.adaic.org/resources/add_content/standards/05aarm/html/AA-B-2.html
[7] http://www.ada-auth.org/standards/12rm/html/RM-B-3.html
[8] http://www.ada-auth.org/standards/12rm/html/RM-B-3-1.html

**FUSE & the FUSE driver** FUSE is a software interface that allows running filesystem code in userspace, with FUSE bridging the gap between the filesystem and the kernel. This simplifies the development of filesystems, because access to the kernel and modification of kernel code is not necessary. FUSE allows a filesystem to be developed iteratively; i.e., first it can be implemented and tested with FUSE, and later connected to a kernel if needed.

To implement a filesystem with FUSE, the code needs to be linked with the FUSE library (libfuse), and a driver must be written to specify the filesystem's handler functions for various operations. As FUSE is written in C, the driver for AdaFS is currently also written in C, with a wrapper in Ada to convert values between C types and Ada types. FUSE specifies a **struct** with pointers to functions that should be written by the programmer for the specific filesystem they are implemented. The library also provides, among others, a function to fill file entries into a buffer, a **struct** to store open file information, and a function to get the context of the current operation (such as the PID requesting the operation). Listing 6 shows an example from the driver, with an implementation of the open file operation.

```c
#define FUSE_USE_VERSION 31
#include <fuse.h>
// Declare the external filesystem open function written in Ada
extern int ada_open(const char *path, pid_t pid);

// The driver's open function
int adafs_open(const char *path, struct fuse_file_info *finfo) {
  pid_t pid = fuse_get_context()->pid;
  int fd = ada_open(path, pid);
  finfo->fh = fd;
  return 0;
}

// Register the function with FUSE
static struct fuse_operations adafs_ops = {
  .open = adafs_open
};

int main(int argc, char **argv) {
  ...
  return fuse_main(argc, argv, &adafs_ops, NULL);
}
```

*Listing 6: FUSE driver implementation of* open

**Formal verification** Unfortunately, much of the code in its current form is not amenable to formal verification. These are namely the parts involving file input and output, and functions that work with C types (i.e. the FUSE driver). However, large parts of filesystem logic *are* formally verifiable. Therefore, the code base was split into two distinct packages: the *adafs* package, which contains filesystem logic that is strictly in the SPARK language, and the *disk* package, which contains unverifiable elements such as disk I/O. The *adafs* package does not include any specifics about the type of disk being used, as the *disk* interface hides implementation details. Thus, when needed, and when an alternative is found, the *disk* package can simply be replaced with a verifiable implementation that exposes an identical interface.

For the parts that are formally verifiable, two types of contracts are available: functional and data contracts. Functional contracts describe how a subprogram should function; that is, the

pre- and post-conditions for a given subprogram. They are written as boolean predicate logic expressions. Pre-conditions are evaluated before entry into the subprogram, and post-conditions are evaluated after exit from the subprogram (and can therefore mention the subprogram's result). SPARK can check these conditions at each call site to ensure that no subprogram call violates the conditions, and that the output(s) are shown to be conformant with the specification (the returned result for a function, and the **out** or **in out** parameters for a procedure).

The second type of contract available are data contracts. SPARK conducts flow analysis, which models the flow of information during a subprogram's execution. It checks for uninitialized variables, ineffective statements, and incorrect parameter modes. It is possible to specify which global variables are read, written, or both read and written in the subprogram, using the Global aspect. If no global variables are used, the value of the aspect is set to **null**. It is also possible to specify data dependencies between a subprogram's inputs and outputs.

For example, Listing 7 shows a function to get an entry from the process table, which specifies the functional and data contracts to be fulfilled for the function. The Global aspect specifies that the function only depends on the value of the package variable tab for input. The Depends aspect states that the result of the function only depends on the tab and pid variables (that is, the variable stated in the Global aspect, and the parameter of the function). The post-condition states that the is_null component of the returned variant record will be set to True if there is no entry in tab for the provided PID; otherwise, the inode number of the PIDs working directory will be non-zero. With the SPARK toolchain, we can verify that these constraints are all satisfied.

```
function get_entry (pid : tab_range) return entry_t with
  Global => (input => tab),
  Depends => (get_entry'Result => (tab, pid)),
  Post => (if tab(pid).is_null
           then get_entry'Result.is_null
           else get_entry'Result.workdir > 0);
```

*Listing 7: Functional and data contracts*

# 5 Results & analysis

- Include the formal verification report, what's verified in relation to CWE numbers.
- Add some performance analysis. Maybe timing? Try to do some common filesystem tasks & see how it performs?
- An idea is to try to test the speed of operations, the key is to show what difference the formal verification makes in terms of runtime.

# 6 Conclusion

Summary and concluding remarks, including possible future work.

# References

[1] *Ext4 file system tree*, `https://git.kernel.org/pub/scm/linux/kernel/git/tytso/ext4.git/`, Accessed on: 2020-06-23.

[2] D. M. Ritchie, "The development of the c language," in *The Second ACM SIGPLAN Conference on History of Programming Languages*, ser. HOPL-II, Cambridge, Massachusetts, USA: Association for Computing Machinery, 1993, pp. 201–208, ISBN: 0897915704. DOI: 10.1145/154766.155580. [Online]. Available: https://doi.org/10.1145/154766.155580.

[3] CERT Division, "2001 CERT advisories," Carnegie Mellon University, Tech. Rep., 2017.

[4] B. Ray, D. Posnett, P. Devanbu, and V. Filkov, "A large-scale study of programming languages and code quality in github," *Commun. ACM*, vol. 60, no. 10, pp. 91–100, Sep. 2017, ISSN: 0001-0782. DOI: 10.1145/3126905. [Online]. Available: https://doi.org/10.1145/3126905.

[5] WhiteSource, "What are the most secure programming languages?" WhiteSource Software, Tech. Rep., 2019, Accessed on: 2020-07-02.

[6] M. Cai, H. Q. Huang, and J. Huang, "Understanding security vulnerabilities in file systems," in *APSys '19*, 2019.

[7] B. Milewski, *SafeD*, https://dlang.org/articles/safed.html, Accessed on: 2020-07-03.

[8] R. Bagnara, A. Bagnara, and P. M. Hill, "The misra c coding standard and its role in the development and analysis of safety- and security-critical embedded software," *ArXiv*, vol. abs/1809.00821, 2018.

[9] P. Cuoq, F. Kirchner, N. Kosmatov, V. Prevosto, J. Signoles, and B. Yakobowski, "Frama-c - a software analysis perspective," in *SEFM*, 2012.

[10] D Language Foundation, *Welcome to D*, https://tour.dlang.org/, Accessed on: 2020-07-03.

[11] ——, *Contract programming*, https://dlang.org/spec/contracts.html, Accessed on: 2020-07-03.

[12] D. Nadlinger, "Purity in D," May 2012, Accessed on: 2020-07-03.

[13] G. Hoare, *Technology from the past come to save the future from itself*, http://venge.net/graydon/talks/intro-talk-2.pdf, Accessed on: 2020-07-03, Jul. 2010.

[14] S. Klabnik and C. Nichols, *The Rust Programming Language*. No Starch Press, Aug. 2019.

[15] *Coq reference manual*, https://coq.inria.fr/distrib/current/refman/, Accessed on: 2020-07-03.

[16] G. Schellhorn, G. Ernst, J. Pfähler, D. Haneberg, and W. Reif, "Development of a verified flash file system," in *ABZ*, 2014.

[17] G. Ernst, G. Schellhorn, D. Haneberg, J. Pfähler, and W. Reif, "A formal model of a virtual filesystem switch," in *SSV*, 2012.

[18] G. Ernst, J. Pfähler, G. Schellhorn, and W. Reif, "Inside a verified flash file system: Transactions and garbage collection," in *VSTTE*, 2015.

[19] S. Amani, A. Hixon, Z. Chen, C. Rizkallah, P. Chubb, L. O'Connor, J. Beeren, Y. Nagashima, J. Lim, T. Sewell, J. Tuong, G. Keller, T. C. Murray, G. Klein, and G. Heiser, "COGENT: Verifying high-assurance file system implementations," in *ASPLOS '16*, 2016.

[20] D. Fryer, K. Sun, R. Mahmood, T. Cheng, S. Benjamin, A. Goel, and A. D. Brown, "Recon: Verifying file system consistency at runtime," *TOS*, vol. 8, 15:1–15:29, 2012.

[21] H. Chen, D. Ziegler, A. Chlipala, M. F. Kaashoek, E. Kohler, and N. Zeldovich, "Specifying crash safety for storage systems," in *HotOS*, 2015.

[22] H. Chen, T. Chajed, A. Konradi, S. Wang, A. M. Ileri, A. Chlipala, M. F. Kaashoek, and N. Zeldovich, "Verifying a high-performance crash-safe file system using a tree specification," *Proceedings of the 26th Symposium on Operating Systems Principles*, 2017.

[23] H. Sigurbjarnarson, J. Bornholt, E. Torlak, and X. Wang, "Push-button verification of file systems via crash refinement," in *12th USENIX Symposium on Operating Systems Design and Implementation (OSDI 16)*, Savannah, GA: USENIX Association, Nov. 2016, pp. 1–16, ISBN: 978-1-931971-33-1. [Online]. Available: https://www.usenix.org/conference/osdi16/technical-sessions/presentation/sigurbjarnarson.

[24] T. Chajed, J. Tassarotti, M. F. Kaashoek, and N. Zeldovich, "Argosy: Verifying layered storage systems with recovery refinement," in *Proceedings of the 40th ACM SIGPLAN Conference on Programming Language Design and Implementation*, ser. PLDI 2019, Phoenix, AZ, USA: Association for Computing Machinery, 2019, pp. 1054–1068, ISBN: 9781450367127. DOI: 10.1145/3314221.3314585. [Online]. Available: https://doi.org/10.1145/3314221.3314585.

[25] AdaCore and Altran UK Ltd, *SPARK 2014 reference manual*, http://docs.adacore.com/live/wave/spark2014/html/spark2014_rm/index.html, Accessed on: 2020-06-26.

[26] A. Tanenbaum, *Operating systems: design and implementation*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 1997, ISBN: 978-0136386773.

[27] *History of MINIX 3*, https://wiki.minix3.org/doku.php?id=www:documentation:read-more, Accessed on: 2020-06-26, 2014.

[28] J. Barnes, *Programming in Ada 2012*. Cambridge: Cambridge University Press, 2014, ISBN: 978-1-107-42481-4.