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Filtered Iterators For Safe and Robust Programs in RIFL

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Abstract

We present a new language construct, *filtered iterators*, for safe and robust input processing. Filtered iterators are designed to eliminate many common input-processing errors while enabling robust continued execution. The design is inspired by (a) observed common input-processing errors and (b) continued execution strategies that are implemented by developers fixing input validation errors. Filtered iterators decompose inputs into input units, atomically and automatically discarding units that trigger errors. Statistically significant results from a developer study highlight the difficulties that developers encounter when developing input-processing code using standard language constructs. These results also demonstrate the effectiveness of filtered iterators in eliminating many of these difficulties and enabling developers to produce safe and robust input-processing code.

1. Introduction

We present the design and evaluation of a new programming language construct, *filtered iterators*, for safe and robust input file processing. To target the problem of prevalent defects and security vulnerabilities in input-processing code, filtered iterators provide continued successful execution in the face of otherwise fatal or exploitable errors and emulate the effect of observed strategies from human developers fixing previous input-processing defects. Filtered iterators are designed to substantially simplify the development of safe and robust input-processing code.

We implement filtered iterators in the Robust Input Filtering Language (RIFL). We empirically evaluate the effectiveness of RIFL in a study in which matched pairs of developers develop input-processing programs with and without filtered iterators. The statistically significant results show that the use of filtered iterators produces code with fewer defects overall, fewer fatal defects, fewer crashes, and fewer conditional clauses (reflecting the reduced complexity of code). Moreover, the use of filtered iterators, by construction, completely eliminates many common sources of defects and security vulnerabilities.

Many past language design efforts have been driven by abstract philosophical goals such as simplicity [74, 79], orthogonality and consistency [76], generality [55], modularity [78], data abstraction [44], supporting analogies with the

way people interact with the physical world [20, 32, 74], and enabling people to communicate with computers using math [9, 41, 50] or an approximation of English [60]. The design of filtered iterators, in contrast, was driven by the goal of eliminating a specific class of problems empirically evident by examining the development histories of existing software projects to understand the mistakes developers repeatedly make using existing languages. And instead of justifying the design with appeals to abstract philosophical principles, we justify the RIFL design via experiments that provide statistically significant empirical evidence for the benefits that it provides.

1.1 Main Concept

The key RIFL filtered iterator construct, the *inspect* construct, splits the input into input units, then iterates over the input units. Example input units include lines in a text file, packets in a network traffic capture file, user files in an archive, and images in an animation. Each iteration is an atomic (all-or-nothing) transaction that processes one input unit. RIFL discards *bad* input units (input units that trigger errors), enabling the program to continue processing the remaining input units as if the discarded input units had never existed.¹ RIFL therefore uses the program itself to find and filter bad input units. Direct benefits of filtered iterators include:

- **Survival:** Filtered iterators prevent program crashes and enable successful continued execution by automatically discarding bad input units that trigger fatal errors or target certain classes of security vulnerabilities.
- **Simplified Development:** Filtered iterators simplify software development by eliminating the need for many explicit checks and error-handling code. Developers can simply omit any check—and the associated error-handling code—that is otherwise required to prevent the program from crashing. Atomic execution also eliminates resource leaks that would otherwise occur when aborted sub-computations neglect to appropriately reclaim allocated resources [51].

¹To help developers debug their programs, the RIFL runtime generates a log that contains all errors that occurred during execution.

- **Simplified Code:** The elimination of explicit checks and error-handling code simplifies the resulting implementation, enhancing the clarity and maintainability of the resulting program.
- **Fast Prototyping:** RIFL enables developers to write the main program logic quickly, without worrying about uncommon input units that may trigger errors. The RIFL runtime produces outputs for the input units that the program can process successfully.

1.2 Design Rationale

Input Processing Defects: RIFL targets input-processing defects, in part, because they occur frequently in practice and often have serious consequences such as security vulnerabilities and program failures [1, 10, 46, 46, 48, 49, 61, 62, 68, 72, 81]. Many of these defects correspond to uncommon corner cases that developers simply overlook. The consequences can be especially severe for programs exposed to potentially malicious inputs that purposefully target defects that well formed or anticipated inputs do not expose.

Continued Execution: RIFL’s focus on continued execution by discarding bad input units is motivated, in part, by the empirical observation that human developers often take precisely this approach when fixing input-processing defects. Specifically, many human bug fixes for null dereference and divide-by-zero errors do not throw an exception or exit the program. They instead nullify the computation associated with the current input unit and continue on to process subsequent input units [46, 48]. For example, fixes to errors CVE-2013-2483, CVE-2012-4286, CVE-2012-4285, CVE-2012-1143, CVE-2012-4507, and CVE-2011-4153 in the CVE database [1] all exhibit this pattern. There are a variety of situations in which this continued execution provides important advantages:

- **Useful Partial Results:** For many computations, results computed from a subset of the input units are far preferable to a computation that simply terminates when it encounters a bad input unit [48]. This property may be particularly relevant when the input file contains multiple largely independent input units, such as multiple network packets in a network capture file [6, 23] or multiple images in an image file [3, 11, 37]. Many of the bug fixes discussed above are specifically designed to enable the program to provide useful partial results in the face of bad input units [48]. Systems for approximate scientific and big data computing often provide mechanisms that increase robustness by discarding bad computations [22, 56]. These mechanisms enable programs to deliver useful partial results even if the program cannot successfully process all input units [22, 56].
- **Safety Critical Systems:** Terminating a safety critical system can have catastrophic results. The alternative of terminating and attempting to reboot can be impractical: (a) A bad input unit may persist in a file that the system

reads when it reboots, preventing the system from successfully rebooting. Such an error was present in the Center TRACON Automation System (CTAS) air-traffic control software [25]. (b) The time required to reboot, reacquire data, and re-calibrate the system may be unacceptable. This is the case for the CTAS air traffic control system. (c) It may be too difficult to recalculate critical values. This reason was explicitly cited in the Ariane-5 disaster report [29]. In these situations, continued execution, even with potentially reduced functionality, is far preferable to termination.

Many language implementations [28, 34, 59] check for conditions such as out of bounds accesses and null dereferences. If the check fires, the implementations typically either terminate the computation [28, 59] or throw an exception [34], which also typically terminates the computation when the exception propagates up to the default handler. In contrast to these mechanisms that terminate the program, RIFL’s continued execution is designed to emulate the bug fixes that human developers produce in practice to maximize program utility via robust continued execution [48].

1.3 Contributions

This paper makes the following contributions.

- **Filtered Iterators:** We present filtered iterators, a novel control structure that partitions input files into input units and discards bad input units atomically and automatically. The goal is to enable robust continued execution without the need to consider or develop code that handles error conditions that uncommon corner-case inputs would trigger.
- **Empirical Evaluation:** We present results from an empirical evaluation of filtered iterators in RIFL. This evaluation is based on experiments that use paired human developers to test hypotheses regarding the ability of RIFL to deliver smaller, more robust programs with fewer defects. The statistically significant results highlight (a) the difficulties that developers face when developing input-processing code using standard constructs and (b) the effectiveness of filtered iterators in eliminating many of these difficulties. In our study, programs from developers using filtered iterators had a total of six defects, none fatal. The paired control group, in contrast, produced programs with a total of 33 defects, 18 fatal, with every program containing at least two fatal defects. We verified the exercisable presence of every defect—with the exception of the defects related to memory allocation failures and memory leaks, which we identified by a code analysis—by developing an input file that triggered the defect. We also briefly discuss our experience developing RIFL programs for a variety of input formats including the PCAP, PNG, ZIP, JSON, and OBJ formats.

```

Img1 2 2 2 1234
Img2 2 4 4 1234567890123456
CharS b 2 2 1234
CharPix 2 2 2 12a4
BufOvfVeryLongName 2 2 2 1234
2 2 2 1234
Div0S 0 2 2 1234
Div0H 2 0 2
HeapOvf 2 60000 1000 1234
BufOvfInt 2 16 268435457 12345678901234567890
Img3 2 1 2 12
Img4 3 3 4 123456789012

```

Figure 1: Example input for thumbnail programs

This paper advocates an empirical approach to programming language design. The field has matured to the point in which the specific problems that developers face, and the characteristics of the fixes they apply in response to these problems, are now becoming clear with experience. Designing constructs with the benefit of this experience, and then experimentally evaluating the success or failure of these constructs in ameliorating the targeted problems, can be one productive way to design new language constructs.

2. Example

A key principle of RIFL is to encourage writing only common-case code and handling errors implicitly with filtered iterators. To illustrate this idea, we contrast two implementations of a bitmap thumbnail generator program. The first implementation uses conventional language constructs to handle errors *explicitly*. The second implementation uses RIFL filtered iterators to handle errors *implicitly*.

Program Functionality: The thumbnail program uses the following algorithm to average the values of neighboring pixels. Given a scaling factor s , the thumbnail for an image of height h and width w has height $\lfloor h/s \rfloor$ and width $\lfloor w/s \rfloor$. The value of the pixel in row i and column j of the thumbnail is the floor of the average of the values of all pixels in the s^2 square area between rows $i \cdot s \dots (i \cdot s + s - 1)$ and columns $j \cdot s \dots (j \cdot s + s - 1)$ of the original image.

Program Input: Figure 1 presents an example input file. The input file contains lines that describe original images. Each line describes an original image with the following components, separated by a single space character: (a) A string that describes the image name. This string contains no space or newline characters and is 1–10 characters long. (b) An integer, s , that represents the scaling factor. (c) An integer, h , that represents the original image height. (d) An integer, w , that represents the original image width. (e) $h \cdot w$ consecutive digits that each represents the color of a pixel in the original image, ranging from ‘0’...‘9’. The pixels represent the image by forming a matrix of h rows and w columns. We order the pixels as follows: inside each row, pixels are ordered from left to right; the rows are each grouped together and ordered from top to bottom.

```

Img1 2
Img2 3543
Img3
Img4 3

```

Figure 2: Example output for thumbnail programs

Program Output: Figure 2 presents the example output. Each line describes a thumbnail image with the following components, separated by a single space character: (a) The image name. (b) $\lfloor h/s \rfloor \lfloor w/s \rfloor$ digits that each represents the value of a pixel in the thumbnail.

Robustness: Like other image file formats [3, 11, 37], the input files in our example may contain multiple images. To maximize the utility of the program, an image that triggers errors should not prevent the program from generating thumbnails for other images.

The example input in Figure 1 contains invalid lines that do not conform to the input specification. Images CharS and CharPix contain illegal characters in the scaling factor and the pixels, respectively. Image BufOvfVeryLongName’s name is too long. In the line that follows, the image name is missing. Image Div0S’s scaling factor is zero, which is undefined for thumbnail generators.

There are other lines in the example input that satisfy the specification but may still trigger errors in implementations with defects. Image Div0H contains an empty image. Image HeapOvf’s dimensions may be too large to fit the entire image in the heap memory. Image BufOvfInt’s dimensions are so large that the multiplication of the image height and width overflows a 32-bit integer.

The example output in Figure 2 contains thumbnails for all images that do not trigger errors.

2.1 Conventional Version

Figure 3 presents a conventional implementation of the thumbnail generator that handles all errors explicitly. Language keywords are in **bold**. The control structure that loops through images is underlined. Error-handling code is highlighted with colored text, according to the following importance category:

- **Vital** code that prevents crashes is in **red**.
- **Service** code that cleans up resources is in **brown**.
- **Integrity** code that prevents input misinterpretation is in **blue**.
- **Common** code that is part of common engineering practice is in **green**.

Table 1 enumerates all the error-handling code in this implementation. Each row describes a piece of code. The columns are as follows: the identifier number (Id), the location (Lines), the importance category (Importance), the functionality (Purpose), and the number of conditional clauses and unconditional statements separated with a slash sign “/” (Count).

Table 1: Error-handling code in the conventional thumbnail program. Each pair of numbers separated by a slash “/” are the numbers of conditional clauses and of unconditional statements.

Id	Lines	Importance	Purpose	Count
1	2–5	integrity	flush trailing bytes for current unit (helper function)	1 / 4
2	10	integrity	avoid mixing bad units with following units	0 / 1
3	11	integrity	identify bad units	0 / 1
4	18	common	exit on invalid input files	1 / 1
5	20	vital	avoid null array accesses	1 / 1
6	22 (bad=0;)	integrity	default to good units	0 / 1
7	24 (x<0)	integrity	identify incomplete units at the ends of files	1 / 0
8	24 (x=='\n')	integrity	avoid mixing bad units with following units	1 / 0
9	24 (i>=10)	vital	avoid out-of-bound array accesses	1 / 0
10	25	integrity	skip bad units	0 / 2
11	29 (bad)	integrity	skip bad units	1 / 2
12	32 (s<=0, h<=0)	vital	avoid divisions by zero	2 / 0
13	32 (w<=0)	integrity	identify malformed units	1 / 0
14	32 ((h*w)/h!=w)	vital	avoid integer overflows and out-of-bound array accesses	1 / 0
15	33	integrity	skip bad units	0 / 2
16	36	vital	avoid null array accesses	1 / 2
17	38 (!bad)	integrity	avoid mixing bad units with following units	1 / 0
18	42	integrity	identify bad units	0 / 2
19	47	integrity	avoid mixing bad units with following units	0 / 1
20	48 (bad)	integrity	skip bad units	1 / 1
21	48 (free_ec(pix))	service	avoid memory leak on bad units	0 / 1

2.2 RIFL Version

None of this error-handling code is needed in the RIFL version of the thumbnail generator in Figure 4. This implementation has the same functionality as the conventional version. Unlike the conventional version, the RIFL version uses an `inspectt` loop to implicitly and atomically discard any input units that violate assertions or trigger other errors during an iteration.

RIFL’s `inspectt` construct implements filtered iterators for text input formats. The (simplified) structure of an `inspectt` loop is as follows.

```
inspectt (e, f, du) { ... }
```

This loop iterates through input units in a text file `f` while expression `e` evaluates to “true”. A delimiter `du` defines the boundaries between input units.

The RIFL runtime supports `inspectt` loops as follows. Like conventional `while` loops, an `inspectt` loop repeatedly executes a code block as long as a given condition holds. Unlike `while` loops, an `inspectt` loop additionally flushes inputs based on the delimiters. The `inspectt` loop avoids all detectable errors by skipping bad input units. RIFL processes each input unit *atomically* in each iteration, so that the updates from processing each input unit either commit or completely abort.

Eliminated Checks: We next discuss the checks and statements that are required in the conventional version but are redundant in the RIFL version. Checks #9, #12, #14, and #16, which are vital in the conventional version, are unnecessary here because the RIFL runtime implicitly triggers an error on failed heap allocations, out-of-bound array accesses,

and divisions by zero. The `inspectt` loop starting from line 13 implicitly handles all these errors by discarding bad input units atomically. Check #5 is also unnecessary because a failed heap allocation on line 12 aborts the program immediately. Specifically, if the conventional version omits any of the vital error-handling code, the program would crash from bad inputs that trigger errors:

- **Out-of-bound array access:** Without check #9, the conventional version writes beyond array name on line 27 when an image name is longer than the array size.
- **Integer overflow and out-of-bound array access:** Without check #14, the conventional version writes beyond array `pix` on line 43 with carefully chosen image dimensions that cause the multiplication on line 35 to overflow the integer representation. This integer overflow can cause the program to allocate an array `pix` that is smaller than expected.
- **Division by zero:** Without check #12, the conventional version triggers division-by-zero errors on line 32 or inside the code for line 50 when an image contains a zero height or a zero scaling factor.
- **Null array access:** Without check #16, the conventional version writes to a null array on line 43 when the heap allocation fails on line 35. Without check #5, the conventional version writes to a null array on line 27 when the memory allocation on line 19 fails.

Apart from freeing the developers from having to write otherwise vital error-handling code, RIFL also eliminates the need for other important code in the conventional version. Statement #21 is unnecessary in the RIFL version be-

```

1 f=fopen("images.txt");
2 func flush (x) {
3   while (x>=0 && x!='\n') { x=read(f); }
4   return 0;
5 }
6 func rdint () {
7   x=0; dgt=read(f);
8   while (dgt!=' ') {
9     if (dgt<'0' || dgt>'9') {
10      _=seek(f,pos(f)-1);
11      return -1;
12    }
13    x=x*10+(dgt-'0'); dgt=read(f);
14  }
15  return x;
16 }
17 main {
18   if (!valid(f)) { exit(1); }
19   name=malloc(10);
20   if (!valid(name)) { exit(1); }
21   while (!end(f)) {
22     bad=0; i=0; x=read(f);
23     while (x!=' ') {
24       if (x<0 || x=='\n' || i>=10) {
25         bad=1; break;
26       }
27       name[i]=x; i=i+1; x=read(f);
28     }
29     if (i<=0 || bad) { _=flush(x); continue; }
30     while (i<10) { name[i]=0; i=i+1; }
31     s=rdint(); h=rdint(); w=rdint();
32     if (s<=0 || h<=0 || w<=0 || (h*w)/h!=w) {
33       _=flush(0); continue;
34     }
35     pix=malloc(h*w);
36     if (!valid(pix)) { _=flush(0); continue; }
37     i=0;
38     while (i<h && !bad) {
39       j=0;
40       while (j<w) {
41         x=read(f);
42         if (x<'0' || x>'9') { bad=1; break; }
43         pix[i*w+j]=x; j=j+1;
44       }
45       i=i+1;
46     }
47     _=flush(x);
48     if (bad) { free(pix); continue; }
49     print(name); print(' ');
50     // « compute and print averages, code omitted »
51     print('\n'); free(pix);
52   }
53   free(name);
54   return 0;
55 }

```

Figure 3: A conventional thumbnail implementation

cause the `inspectt` loop discards bad input units atomically, preventing a memory leak in this situation. Combining error handling with iterators, RIFL also eliminates the need to explicitly maintain the integrity of input units as in (a) statements #1, #2, #3, #6, #10, #15, #18, and #19, or (b) checks #7, #8, #11, #13, #17, and #20. On the other hand, the conventional version would suffer from omitting these important code:

- **Memory leak:** Without statement #21, the conventional version leaks memory on images with corrupted pixel values. Memory leaks degrade the quality of service and may result in allocation failures.

```

1 f=fopen("images.txt");
2 func rdint () {
3   x=0; dgt=read(f);
4   while (dgt!=' ') {
5     assert(dgt>='0' && dgt<='9');
6     x=x*10+(dgt-'0'); dgt=read(f);
7   }
8   return x;
9 }
10
11 main {
12   name=malloc(10);
13   inspectt (!end(f),f,'\n') {
14     i=0; x=read(f);
15     while (x!=' ') {
16       name[i]=x; i=i+1; x=read(f);
17     }
18     assert(i>=1);
19     while (i<10) { name[i]=0; i=i+1; }
20     s=rdint(); h=rdint(); w=rdint();
21     pix=malloc(h*w);
22     i=0;
23     while (i<h) {
24       j=0;
25       while (j<w) {
26         x=read(f);
27         assert(x>='0' && x<='9');
28         pix[i*w+j]=x; j=j+1;
29       }
30       i=i+1;
31     }
32     print(name); print(' ');
33     // « compute and print averages, code omitted »
34     print('\n'); free(pix);
35   }
36   free(name);
37   return 0;
38 }

```

Figure 4: A RIFL thumbnail implementation

- **Input misinterpretation:** Other code is necessary for the integrity of input units on errors. Code #1, #2, #8, #10, #15, #17, #18, and #19 isolate bad input units from other input units. Code #3, #6, #7, #11, #13, and #20 detect bad input units.
- **Common practice:** Code #4 checks whether the opening operation on line 1 succeeded. Developers should check this error early, even if missing this check may not cause immediate crashes.

The RIFL version is shorter and significantly simpler than the conventional version. This fact is consistent with the intuition that filtered iterators can simplify the implementation of robust programs.

3. The RIFL Language

RIFL is a standard imperative language augmented with two `inspect` loop constructs: the `inspectt` construct for text files and the `inspectb` construct for binary files.

3.1 Syntax

Figure 5 presents the syntax of RIFL. The structure of `inspect` loops for text inputs is

```
inspectt (e, f, du, ds) { ... }
```

```

Prog := Stmt | func  $q(x)$ {Stmt;return  $y$ };Prog
Exp :=  $n$  |  $x$  | Exp op Exp |  $a$ [Exp] | valid( $a$ ) | end( $f$ ) | pos( $f$ )
Stmt :=  $x = \text{Exp}$  |  $a = \text{malloc}(\text{Exp})$  | free( $a$ ) |  $a[\text{Exp}] = \text{Exp}$ 
      |  $x = q(\text{Exp})$  | Stmt; Stmt | if(Exp){Stmt}else{Stmt}
      | while(Exp){Stmt} | inspectt(Exp,  $f$ ,  $d_u$ ,  $d_s$ ){Stmt}
      | inspectb(Exp,  $f$ , Exp, Exp, Exp){Stmt}
      |  $f = \text{opent}(str)$  |  $f = \text{openb}(str)$  | seek( $f$ , Exp)
      |  $x = \text{read}(f)$  | assert(Exp)

 $x, y \in IVar$                  $q \in \text{function names}$ 
 $a, d_u, d_s \in AVar$          $n \in Int$ 
 $f \in FVar$                   $str \in String$ 

```

Figure 5: Abstract syntax

which, while expression e evaluates to “true”, iterates through input units in a text file f . Each loop iteration may access an input unit that consists of the contents of file f up to the end-of-unit delimiters specified in du . The loop terminates when e evaluates to “false”, when the program reads the end-of-sequence delimiters specified in ds , or when the program reaches the end of file f .

The structure of inspect loops for binary inputs is

```
inspectb ( $e$ ,  $f$ ,  $o$ ,  $w$ ,  $c$ ) { ... }
```

which, while expression e evaluates to “true”, iterates through input units in a binary file f . Each loop iteration may access an input unit that consists of the contents of file f up to a cutoff position as specified by the parameters o , w , and c . The loop terminates when e evaluates to “false”, when the program reaches the end of an outer-level input unit, or when the program reaches the end of file f . The cutoff position for each input unit is computed as follows. Before each loop iteration, the RIFL runtime identifies the length field in file f using the offset o and the width w . It extracts the value of the length field according to the endianness that the developer specifies when opening file f . The RIFL runtime then precomputes a cutoff position of the current input unit by summing up the current file offset, the value of the length field, and the extra length c .

Atomic Execution and Filtering: In addition to iterating, inspect loops also handle errors by filtering out bad input units. The RIFL runtime includes checks for implicit error conditions such as out-of-bounds accesses, null pointer dereferences, divisions by zero, and memory allocation failures. When an iteration of an inspect loop triggers an error, either because of a failed RIFL check or because of an explicit assertion failure, the RIFL runtime (a) identifies the bad input unit, (b) advances the file pointer past the bad input unit, (c) restores the rest of the program’s state, and (d) restarts the program execution at the start of the next input unit (unless the bad input unit is the last input unit in the file).

Nesting and Recursion: Besides sequential input units, inspect loops can also process complex input structures with nesting and recursion. For example, the Comma Separated Values (CSV) format [63] delimits rows with newline characters and delimits fields inside each row with comma characters. Rows are larger input units and fields are smaller input units. A program that processes CSV files may contain two nested inspect loops, where the outer loop uses the newline delimiter and the inner loop uses the comma delimiter. As another example, the JavaScript Object Notation (JSON) [12] reuses the right brace character as the delimiter for objects across all nesting layers. Objects are input units. A program that processes the JSON format may contain a recursive function where an inspect loop uses the right brace delimiter and parses inner input units by calling the function recursively.

3.2 Operational Semantics

We developed a RIFL interpreter based on the following operational semantics. RIFL’s operational semantics uses the following domain. A state

$$\sigma \in State = Stack \times Heap \times Files \times Disk$$

contains information about the stack memory, the heap memory, the status of opened files and the disk. The stack maps variables to values, which can be integers, file handlers or memory addresses. The heap maps memory addresses to array contents. The file status maps file handlers to file descriptors. The disk maps file names to file contents.

$$Stack = Var \rightarrow Value$$

$$Heap = Addr \rightarrow Data \times Size$$

$$Files = FHndl \rightarrow FDesc$$

$$Disk = FName \rightarrow Data \times Size$$

where $Var = IVar \cup FVar \cup AVar$, $Value = Int \cup FHndl \cup Addr$, $Data = Offs \rightarrow Int$, and $Size = Offs = Int$.

A file descriptor $fd \in FDesc = FName \times Offs \times SOU \times UDesc$ describes the current status of reading an input file, including the file name, the current offset into the file, the starting offset of the current input unit, and an input unit descriptor. $FName = String$, $SOU = Int$. An input unit descriptor $ud \in UDesc = Delim \cup Cutoff$ describes the delimiters in use for text files and the cutoff positions for binary files.

For text files, a delimiter definition $dlim \in Delim = EOU \times EOS \times OSD$ describes three sets of delimiters that identify the boundaries between input units: $dlim = \langle eou, eos, osd \rangle$ where $eou \in EOU = \mathcal{P}(Int)$ is the set of end-of-unit delimiters, $eos \in EOS = \mathcal{P}(Int)$ is the set of end-of-sequence delimiters, and $osd \in osd = \mathcal{P}(Int)$ is the set of outside delimiters that serve nested input units. The next delimiter in the input file, whether it is one in $eou \cup eos \cup osd$ or the end of the file, marks the end of

the current input unit. The set of outside delimiters osd updates at runtime as follows. For single-layer `inspectt` loops and the outermost `inspectt` loops in nested structures, $osd = \emptyset$. For inner `inspectt` loops, osd includes all delimiters in $eor \cup eos$ for all the outer `inspectt` layers, except for those that also appear in $eor \cup eos$ of the current layer. This exception is useful for input formats that reuse delimiters across layers, such as JSON. However, the developer should be careful about reusing delimiters across the hierarchy. Reuse can make delimiters ambiguous, which may cause the program to misinterpret the input structures in the face of delimiter corruptions.

For binary files, a cutoff position $cut \in Cutoff = Int$ describes where the current input unit ends. This value also updates at runtime according to nesting `inspectb` layers.

The relation $\langle e, \sigma \rangle \Downarrow_e \mu$ denotes that evaluating the expression e in state σ yields the result $\mu \in Int \cup \{err\}$. A result $\mu \in Int$ indicates that the evaluation is successful and that the numerical result is μ . A result $\mu = err$ indicates that the evaluation fails, which would then trigger an error in the surrounding statement.

The relation $\langle s, \sigma \rangle \Downarrow_s \xi$ denotes that executing the statement s in the state σ yields the output configuration $\xi \in State \times \{ok, bad\}$. An output configuration $\xi = \langle \sigma', ok \rangle$ indicates that the program execution is successful and that the resulting state is σ' . An output configuration $\xi = \langle \sigma', bad \rangle$ indicates that the program execution triggered an error and that the latest reasonable program state is σ' . In this case, the RIFL runtime would report the error to the surrounding `inspect` loop which would resolve the problem.

3.2.1 Basic Operations

Figures 6–11 present basic operations. Figure 6 presents the semantics for simple expressions. Arithmetic errors and invalid array reads trigger errors in the surrounding statement (`iop-bad`, `ard-null`, `ard-out`). The `valid` predicate tests whether an array variable is not null (`avalid-t`, `avalid-f`). Figure 7 presents the semantics for simple assignments. When assigning a bad expression to a variable, rule (`vwr-bad`) treats the statement as a no-op and reports the error. Figure 8 presents the semantics for arrays. A successful `malloc` statement allocates a space of the specified size in the heap, initializes all the elements to 0, and sets the array variable to the heap address (`malloc-ok`). A successful `free` statement deallocates the space from the heap and resets the array variable to null (`free-ok`). A successful assignment to an array element changes the specified element in the heap (`awr-ok`). On bad expressions, invalid `malloc` parameters, allocation failures, null array frees, null array accesses, or out-of-bounds array writes, rules (`malloc-bad`, `awr-bad`, `malloc-neg`, `malloc-ovf`, `free-null`, `awr-null`, `awr-out`) treat the statement as a no-op and reports the error. Figure 9 presents the semantics for function calls using the following helper functions:

$$\begin{array}{r}
\overline{\langle n, \sigma \rangle \Downarrow_e n} \quad (\text{int}) \\
\overline{\langle x, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \sigma_S(x)} \quad (\text{ivar}) \\
\frac{\langle e_1, \sigma \rangle \Downarrow_e u_1 \quad \langle e_2, \sigma \rangle \Downarrow_e u_2 \quad u_1 \text{ op } u_2 = v}{\langle e_1 \text{ op } e_2, \sigma \rangle \Downarrow_e v} \quad (\text{iop-ok}) \\
\frac{\langle e_1, \sigma \rangle \Downarrow_e u_1 \quad \langle e_2, \sigma \rangle \Downarrow_e u_2 \quad u_1 \text{ op } u_2 = \perp}{\langle e_1 \text{ op } e_2, \sigma \rangle \Downarrow_e err} \quad (\text{iop-bad}) \\
\frac{\sigma_S(a) = \text{null}}{\langle a[e], \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e err} \quad (\text{ard-null}) \\
\frac{\sigma_S(a) \neq \text{null} \quad \langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad \sigma_H(\sigma_S(a)) = \langle \gamma, n \rangle \quad u < 0 \vee u \geq n}{\langle a[e], \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e err} \quad (\text{ard-out}) \\
\frac{\sigma_S(a) \neq \text{null} \quad \langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad \sigma_H(\sigma_S(a)) = \langle \gamma, n \rangle \quad 0 \leq u < n}{\langle a[e], \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \gamma(u)} \quad (\text{ard-ok}) \\
\frac{\sigma_S(a) \neq \text{null}}{\langle \text{valid}(a), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{true}} \quad (\text{avalid-t}) \\
\frac{\sigma_S(a) = \text{null}}{\langle \text{valid}(a), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{false}} \quad (\text{avalid-f})
\end{array}$$

Figure 6: Semantics for simple expressions

$$\begin{array}{r}
\frac{\langle e, \sigma \rangle \Downarrow_e err}{\langle x = e, \sigma \rangle \Downarrow_s \langle \sigma, bad \rangle} \quad (\text{vwr-bad}) \\
\frac{\langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u}{\langle x = e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto u], \sigma_H, \sigma_F, \sigma_D \rangle, ok \rangle} \quad (\text{vwr-ok})
\end{array}$$

Figure 7: Semantics for assignments

$$\begin{array}{r}
\frac{\langle s_1, \sigma \rangle \Downarrow_s \langle \sigma', bad \rangle}{\langle s_1; s_2, \sigma \rangle \Downarrow_s \langle \sigma', bad \rangle} \quad (\text{seq-bad}) \\
\frac{\langle s_1, \sigma \rangle \Downarrow_s \langle \sigma', ok \rangle \quad \langle s_2, \sigma' \rangle \Downarrow_s \xi}{\langle s_1; s_2, \sigma \rangle \Downarrow_s \xi} \quad (\text{seq-prgr}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e err}{\langle \text{if}(e)\{s_1\}\text{else}\{s_2\}, \sigma \rangle \Downarrow_s \langle \sigma, bad \rangle} \quad (\text{if-bad}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle s_1, \sigma \rangle \Downarrow_s \xi}{\langle \text{if}(e)\{s_1\}\text{else}\{s_2\}, \sigma \rangle \Downarrow_s \xi} \quad (\text{if-t}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{false} \quad \langle s_2, \sigma \rangle \Downarrow_s \xi}{\langle \text{if}(e)\{s_1\}\text{else}\{s_2\}, \sigma \rangle \Downarrow_s \xi} \quad (\text{if-f}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e err}{\langle \text{while}(e)\{s\}, \sigma \rangle \Downarrow_s \langle \sigma, bad \rangle} \quad (\text{while-bad}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{false}}{\langle \text{while}(e)\{s\}, \sigma \rangle \Downarrow_s \langle \sigma, ok \rangle} \quad (\text{while-end}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle s, \sigma \rangle \Downarrow_s \langle \sigma', bad \rangle}{\langle \text{while}(e)\{s\}, \sigma \rangle \Downarrow_s \langle \sigma', bad \rangle} \quad (\text{while-body}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle s, \sigma \rangle \Downarrow_s \langle \sigma', ok \rangle \quad \langle \text{while}(e)\{s\}, \sigma' \rangle \Downarrow_s \xi}{\langle \text{while}(e)\{s\}, \sigma \rangle \Downarrow_s \xi} \quad (\text{while-prgr})
\end{array}$$

Figure 10: Semantics for basic control structures

$$\begin{array}{c}
\frac{\langle e, \sigma \rangle \Downarrow_e \text{err}}{\langle a = \text{malloc}(e), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{malloc-bad}) \quad \frac{\langle e, \sigma \rangle \Downarrow_e u \quad u \leq 0}{\langle a = \text{malloc}(e), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{malloc-neg}) \quad \frac{\langle e, \sigma \rangle \Downarrow_e u \quad u > 0 \quad \text{heap allocate}(u) = \perp}{\langle a = \text{malloc}(e), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{malloc-ovf}) \\
\frac{\langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad u > 0 \quad \text{heap allocate}(u) = \text{addr}}{\langle a = \text{malloc}(e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[a \mapsto \text{addr}], \sigma_H[\text{addr} \mapsto \langle [0 \mapsto 0, 1 \mapsto 0, \dots, u-1 \mapsto 0], u \rangle], \sigma_F, \sigma_D \rangle, \text{ok} \rangle} \quad (\text{malloc-ok}) \\
\frac{\sigma_S(a) = \text{null}}{\langle \text{free}(a), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle} \quad (\text{free-null}) \\
\frac{\sigma_S(a) \neq \text{null}}{\langle \text{free}(a), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[a \mapsto \text{null}], \sigma_H[\sigma_S(a) \mapsto \perp], \sigma_F, \sigma_D \rangle, \text{ok} \rangle} \quad (\text{free-ok}) \\
\frac{\sigma_S(a) = \text{null}}{\langle a[e_1] = e_2, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle} \quad (\text{awr-null}) \\
\frac{\sigma_S(a) \neq \text{null} \quad \langle e_1, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{err} \vee \langle e_2, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{err}}{\langle a[e_1] = e_2, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{awr-bad}) \\
\frac{\sigma_S(a) \neq \text{null} \quad \langle e_1, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad \sigma_H(\sigma_S(a)) = \langle \gamma, n \rangle \quad u < 0 \vee u \geq n}{\langle a[e_1] = e_2, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle} \quad (\text{awr-out}) \\
\frac{\sigma_S(a) \neq \text{null} \quad \langle e_1, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u_1 \quad \sigma_H(\sigma_S(a)) = \langle \gamma, n \rangle \quad 0 \leq u_1 < n \quad \langle e_2, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u_2}{\langle a[e_1] = e_2, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H[\sigma_S(a) \mapsto \langle \gamma[u_1 \mapsto u_2], n \rangle], \sigma_F, \sigma_D \rangle, \text{ok} \rangle} \quad (\text{awr-ok})
\end{array}$$

Figure 8: Semantics for arrays

$$\begin{array}{c}
\frac{\langle e, \sigma \rangle \Downarrow_e \text{err}}{\langle x = q(e), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{fn-arg}) \quad \frac{\text{stack allocate}(fr(q)) = \perp}{\langle x = q(e), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{fn-ovf}) \\
\frac{\text{stack allocate}(fr(q)) \neq \perp \quad \langle e, \sigma \rangle \Downarrow_e u \quad \langle \text{body}(q), \langle [arg(q) \mapsto u], \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma'_S, \sigma'_H, \sigma'_F, \sigma'_D \rangle, \text{bad} \rangle}{\langle x = q(e), \sigma \rangle \Downarrow_s \langle \sigma_S, \sigma_H, \sigma'_F, \sigma_D \rangle, \text{bad}} \quad (\text{fn-body}) \\
\frac{\text{stack allocate}(fr(q)) \neq \perp \quad \langle e, \sigma \rangle \Downarrow_e u \quad \langle \text{body}(q), \langle [arg(q) \mapsto u], \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma'_S, \sigma'_H, \sigma'_F, \sigma'_D \rangle, \text{ok} \rangle}{\langle x = q(e), \sigma \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto \sigma'_S(\text{ret}(q))], \sigma'_H, \sigma'_F, \sigma'_D \rangle, \text{ok} \rangle} \quad (\text{fn-prgr})
\end{array}$$

Figure 9: Semantics for function calls

$$\begin{array}{c}
\frac{\langle e, \sigma \rangle \Downarrow_e \text{err}}{\langle \text{assert}(e), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{assert-bad}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{true}}{\langle \text{assert}(e), \sigma \rangle \Downarrow_s \langle \sigma, \text{ok} \rangle} \quad (\text{assert-t}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{false}}{\langle \text{assert}(e), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{assert-f})
\end{array}$$

Figure 11: Semantics for assertions

For each function definition $\text{func } q(x)\{s; \text{return } y\}$,
let $arg(q) \triangleq x$, $body(q) \triangleq s$, $ret(q) \triangleq y$, and
 $fr(q) \triangleq$ size of q 's stack frame.

A successful function call updates the global states and assigns the return value to the receiving variable (**fn-prgr**). If the argument uses a bad expression or if the stack overflows, rules (**fn-arg**, **fn-ovf**) treat the function call as a no-op and report the error. If an error occurs inside the function call, rule (**fn-body**) updates only the file descriptors and then reports the error. Figure 10 presents the semantics for basic control structures. When an error occurs, the program stops executing and reports the error (**seq-bad**, **while-body**). If an inspect loop surrounds these statements, this inspect loop would dis-

card the updates in the current iteration and would restart with the remaining input. Figure 11 presents the semantics for assertions. True assertions are no-ops (**assert-t**); false assertions or bad expressions generate errors (**assert-f**, **assert-bad**).

3.2.2 Filtered Iterators

Figures 12–15 present the semantics for filtered iterators. An inspect loop automatically maintains the file descriptor and other program states, using delimiters for text files and length fields for binary files as follows.

Text input formats: Figures 12 and 13 present the semantics for filtered iterators for text input files, using the following helper functions:

$$\begin{array}{l}
\Omega(a) \triangleq \{j \in \text{Int} \mid \exists i \in \text{Int}, \sigma_H(\sigma_S(a)) = \langle \gamma, n \rangle, \gamma(i) = j\} \\
(a \in \text{AVar}, a \neq \text{null}) \\
\text{returns the set of elements in array } a.
\end{array}$$

$$\begin{array}{l}
\Lambda'(l') \triangleq \underset{k \geq l'}{\text{argmin}} \{k = n' \vee \gamma'(k) \in \text{eos}' \cup \text{osd}'\} \\
(l' = 0, 1, \dots, n') \\
\text{returns the offset of the upcoming delimiter from offset } l'.
\end{array}$$

$$\frac{\sigma_F(\sigma_S(f)) = \langle str, l, sou, ud \rangle \quad \sigma_D(str) = \langle \gamma, n \rangle \quad l = \Lambda(l)}{\langle \text{end}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{true}} \quad (\text{end-t})$$

$$\frac{\sigma_F(\sigma_S(f)) = \langle str, l, sou, ud \rangle \quad \sigma_D(str) = \langle \gamma, n \rangle \quad l < \Lambda(l)}{\langle \text{end}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{false}} \quad (\text{end-f})$$

$$\frac{\sigma_F(\sigma_S(f)) = \langle str, l, sou, ud \rangle}{\langle \text{pos}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e l} \quad (\text{pos})$$

Figure 16: Semantics for input file expressions

An `inspectt` loop updates the starting offset of current input unit, updates the delimiters in use, and advances the offset according to the boundaries of input units (`inspt-prgr`). The loop terminates if the predicate evaluates to “false” (`inspt-end`) or if the program reaches the end of the unit sequence (`inspt-eos`, `inspt-osd`). Situations that end a sequence include reaching one of the explicit d_s delimiters, reaching a delimiter from outer `inspectt` layers, and reaching the end of the file. An `inspectt` loop handles a bad input unit by advancing the offset past the bad unit, restoring all other program states, and recovering the execution (`inspt-dsc-eou`, `inspt-dsc-eos`, `inspt-dsc-osd`). The delimiter arrays and the loop predicate should be valid (`inspt-null`, `inspt-bad`). The two sets of delimiters $\Omega(d_u)$ and $\Omega(d_s)$ should not intersect (`inspt-dupl`).

Binary input formats: Figures 14 and 15 present the semantics for filtered iterators for binary input files, using the following helper function:

$$\text{parseint}(l, u)$$

$$\triangleq \begin{cases} 0, & \text{if } u = 0 \\ \text{the integer value decoded from} & \text{if } u = 1, 2, \dots, n - l + 1 \\ \text{bytes } \gamma(l), \dots, \gamma(l + u - 1), & \end{cases}$$

$$(l = 0, 1, \dots, n)$$

returns the integer value decoded from the u bytes starting from offset l .

An `inspectb` loop updates the starting offset of current input unit, updates the cutoff position, and advances the offset according to the boundaries of input units (`inspb-prgr`). The loop terminates if the predicate evaluates to “false” (`inspb-end`) or if the program reaches the end of the unit sequence (`inspb-eos`). Situations that end a sequence include reaching the cutoff position of the surrounding `inspectb` layer, reaching a zero-length input unit, or reaching a negative length field. An `inspectb` loop handles a bad input unit by advancing the offset past the bad unit, restoring all other program states, and recovering the execution (`inspb-dsc-eou`, `inspb-dsc-eos`). The parameters that identify the length field should be nonnegative (`inspb-neg`). The loop predicate and parameters should be valid (`inspb-bad`).

3.2.3 Explicit File Operations

Figures 16–18 present explicit file operations using the following helper function:

$$\Lambda(l) \triangleq \begin{cases} \text{argmin}\{k = n \vee & \text{if } ud = \langle eou, eos, osd \rangle \\ k \geq l & \in \text{Delim} \\ \gamma(k) \in eou \cup eos \cup osd\}, & \\ \text{cut}, & \text{if } ud = \text{cut} \in \text{Cutoff} \end{cases}$$

$$(l = 0, 1, \dots, n)$$

returns the offset of the upcoming delimiter from offset l for text inputs, and returns the upcoming cutoff position for binary inputs.

Figure 16 presents the semantics for input file expressions. The `end` predicate uses the file size and the input unit descriptors from all the nested `inspect` loop layers to test whether the input file offset is at the end of the current input unit (`end-t`, `end-f`). The `pos` function returns the current offset of the file descriptor (`pos`). Figure 17 presents the semantics for opening input files. A successful `opent` statement sets the file variable to a fresh text file handler (`opent-ok`). A successful `openb` statement sets the file variable to a fresh binary file handler (`openb-ok`). Figure 18 presents the semantics for accessing input files. A successful `seek` statement sets the file offset to the specified position (`sk-ok`). A successful `read` operation assigns the current input byte to the receiving variable and advances the offset in the file descriptor (`frd-ok`). The new position for `seek` must be inside the current input unit (`sk-l`, `sk-r`). Likewise, the developer should not invoke `read` at a delimiter in a text file, at a cutoff position in a binary file, or at the end of the file (`frd-out`). Instead, they should use the `end` predicate to test before reading. To read multiple bytes into an array, the developer may write a loop that reads multiple times. While another operation that is dedicated for this purpose would be expressive, the rules for this operation are complicated and do not add much insight beyond handling array bounds and input unit boundaries.

4. Controlled Experiment

We evaluate the RIFL design with a controlled experiment that uses pairwise comparison [69, 80] to evaluate the use of filtered iterators in program development. We are interested in the following research questions:

- **RQ1:** Does `inspect` reduce program *defects*?
- **RQ2:** Does `inspect` increase program *survivals*?
- **RQ3:** Does `inspect` reduce *wrong outputs*?
- **RQ4:** Does `inspect` reduce *wrong outputs* even if we apply failure-oblivious computing [57] to control group programs?
- **RQ5:** Does `inspect` reduce program *complexity*?

4.1 Methodology

Experimental Design: We first defined an input processing task, specifically, a thumbnail generator for files that may contain multiple images, as in Section 2. We then recruited twelve subjects to write a program that performed the task. These subjects were drawn from the academic population at

$$\begin{array}{c}
\frac{\langle e, \sigma \rangle \Downarrow_e \text{false}}{\langle \text{inspectb}(e, f, o, w, c)\{s\}, \sigma \rangle \Downarrow_s \langle \sigma, \text{ok} \rangle} \quad (\text{inspb-end}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle o, \sigma \rangle \Downarrow_e u_o \quad \langle w, \sigma \rangle \Downarrow_e u_w \quad \langle c, \sigma \rangle \Downarrow_e u_c \quad \sigma = \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{cut} \rangle \\
\sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u_o \geq 0 \quad u_w \geq 0 \quad \text{parseint}(l + u_o, u_w) = v \quad \text{cut} = l \vee u_o = u_w = u_c = 0 \vee v < 0}{\langle \text{inspectb}(e, f, o, w, c)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F[\sigma_S(f)] \mapsto \langle \text{str}, \text{cut}, \text{sou}, \text{cut} \rangle \rangle, \sigma_D \rangle, \text{ok} \rangle} \quad (\text{inspb-eos}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle o, \sigma \rangle \Downarrow_e u_o \quad \langle w, \sigma \rangle \Downarrow_e u_w \quad \langle c, \sigma \rangle \Downarrow_e u_c \quad \sigma = \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{cut} \rangle \\
\sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u_o \geq 0 \quad u_w \geq 0 \quad \text{parseint}(l + u_o, u_w) = v \quad v \geq 0 \quad u_c \geq 0 \quad l + u_o + u_w + v + u_c = \text{cut}' \quad l < \text{cut}' \leq \text{cut} \\
\langle s, \langle \sigma_S, \sigma_H, \sigma_F[\sigma_S(f)] \mapsto \langle \text{str}, l, l, \text{cut}' \rangle \rangle, \sigma_D \rangle \Downarrow_s \langle \langle \sigma'_S, \sigma'_H, \sigma'_F, \sigma'_D \rangle, \text{ok} \rangle \\
\langle \text{inspectb}(e, f, o, w, c)\{s\}, \langle \sigma'_S, \sigma'_H, \sigma'_F[\sigma'_S(f)] \mapsto \langle \text{str}, \text{cut}', \text{sou}, \text{cut}' \rangle \rangle, \sigma'_D \rangle \Downarrow_s \xi}{\langle \text{inspectb}(e, f, o, w, c)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \xi} \quad (\text{inspb-prgr})
\end{array}$$

Figure 14: Semantics for filtered iterators—with good binary inputs

$$\begin{array}{c}
\frac{\langle e, \sigma \rangle \Downarrow_e \text{err} \vee \langle o, \sigma \rangle \Downarrow_e \text{err} \vee \langle w, \sigma \rangle \Downarrow_e \text{err} \vee \langle c, \sigma \rangle \Downarrow_e \text{err}}{\langle \text{inspectb}(e, f, o, w, c)\{s\}, \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{inspb-bad}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle o, \sigma \rangle \Downarrow_e u_o \quad \langle w, \sigma \rangle \Downarrow_e u_w \quad \langle c, \sigma \rangle \Downarrow_e u_c \quad \sigma = \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \\
\sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{cut} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u_o < 0 \vee u_w < 0 \vee u_c < 0}{\langle \text{inspectb}(e, f, o, w, c)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle} \quad (\text{inspb-neg}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle o, \sigma \rangle \Downarrow_e u_o \quad \langle w, \sigma \rangle \Downarrow_e u_w \quad \langle c, \sigma \rangle \Downarrow_e u_c \quad \sigma = \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \\
\sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{cut} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u_o \geq 0 \quad u_w \geq 0 \\
\text{parseint}(l + u_o, u_w) = v \quad v \geq 0 \quad u_c \geq 0 \quad l + u_o + u_w + v + u_c = \text{cut}' \quad \text{cut}' > \text{cut}}{\langle \text{inspectb}(e, f, o, w, c)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F[\sigma_S(f)] \mapsto \langle \text{str}, \text{cut}, \text{sou}, \text{cut} \rangle \rangle, \sigma_D \rangle, \text{ok} \rangle} \quad (\text{inspb-dsc-eos}) \\
\frac{\langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle o, \sigma \rangle \Downarrow_e u_o \quad \langle w, \sigma \rangle \Downarrow_e u_w \quad \langle c, \sigma \rangle \Downarrow_e u_c \quad \sigma = \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \\
\sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{cut} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u_o \geq 0 \quad u_w \geq 0 \\
\text{parseint}(l + u_o, u_w) = v \quad v \geq 0 \quad u_c \geq 0 \quad l + u_o + u_w + v + u_c = \text{cut}' \quad l < \text{cut}' \leq \text{cut} \\
\langle s, \langle \sigma_S, \sigma_H, \sigma_F[\sigma_S(f)] \mapsto \langle \text{str}, l, l, \text{cut}' \rangle \rangle, \sigma_D \rangle \Downarrow_s \langle \sigma', \text{bad} \rangle \\
\langle \text{inspectb}(e, f, o, w, c)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F[\sigma_S(f)] \mapsto \langle \text{str}, \text{cut}', \text{sou}, \text{cut}' \rangle \rangle, \sigma_D \rangle \Downarrow_s \xi}{\langle \text{inspectb}(e, f, o, w, c)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \xi} \quad (\text{inspb-dsc-eou})
\end{array}$$

Figure 15: Semantics for filtered iterators—with bad binary inputs

$$\begin{array}{c}
\frac{\text{file } \text{str} \text{ does not exist}}{\langle f = \text{opent}(\text{str}), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{opent-bad}) \quad \frac{\text{file } \text{str} \text{ does not exist}}{\langle f = \text{openb}(\text{str}), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{openb-bad}) \\
\frac{\text{file } \text{str} \text{ exists}}{\langle f = \text{opent}(\text{str}), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[f \mapsto \text{hndl}], \sigma_H, \sigma_F[\text{hndl} \mapsto \langle \text{str}, 0, 0, \langle \emptyset, \emptyset, \emptyset \rangle] \rangle, \sigma_D \rangle, \text{ok} \rangle} \quad (\text{opent-ok}) \\
\frac{\text{file } \text{str} \text{ exists} \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle}{\langle f = \text{openb}(\text{str}), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[f \mapsto \text{hndl}], \sigma_H, \sigma_F[\text{hndl} \mapsto \langle \text{str}, 0, 0, n \rangle] \rangle, \sigma_D \rangle, \text{ok} \rangle} \quad (\text{openb-ok})
\end{array}$$

Figure 17: Semantics for opening input files

$$\begin{array}{c}
\frac{\langle e, \sigma \rangle \Downarrow_e \text{err}}{\langle \text{seek}(f, e), \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle} \quad (\text{sk-bad}) \\
\frac{\langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad u < \text{sou}}{\langle \text{seek}(f, e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle} \quad (\text{sk-l}) \\
\frac{\langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad \text{sou} \leq u \leq \Lambda(l)}{\langle \text{seek}(f, e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F[\sigma_S(f)] \mapsto \langle \text{str}, u, \text{sou}, \text{ud} \rangle \rangle, \sigma_D \rangle, \text{ok} \rangle} \quad (\text{sk-ok}) \\
\frac{\langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u > \Lambda(l)}{\langle \text{seek}(f, e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle} \quad (\text{sk-r}) \\
\frac{\sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad l = \Lambda(l)}{\langle x = \text{read}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle} \quad (\text{frd-out}) \\
\frac{\sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad l < \Lambda(l)}{\langle x = \text{read}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto \gamma(l)], \sigma_H, \sigma_F[\sigma_S(f)] \mapsto \langle \text{str}, l + 1, \text{ud} \rangle \rangle, \sigma_D \rangle, \text{ok} \rangle} \quad (\text{frd-ok})
\end{array}$$

Figure 18: Semantics for accessing input files

MIT and included both doctoral students and post-doctoral researchers at MIT.

We manually matched pairs of subjects based on educational background, programming experience in the past five years, and knowledge of C/C++. We randomly assigned the two subjects in each pair to either the inspect group or the control group. Both groups performed the programming task using a virtual machine that we prepared for this experiment. We then used the Wilcoxon signed-rank test [77], which tests the location shift of paired samples, to analyze the resulting developer programs.

Independent Variable: The only difference between the two groups was the use of the `inspect` construct: the inspect group used the full RIFL language, while the control group used RIFL without the `inspect` construct, but with standard control flow constructs and error signaling.

Dependent Variables: We collected and analyzed all programs in terms of defects, behavior on a range of inputs, and complexity. We are most interested in the number of total defects.

- **Defects:** To address **RQ1**, we manually analyzed the defects in all programs from the experiment, based on a predefined list of possible defects which we extended during the analysis. Tables 2 and 3 present the lists of possible fatal defects and other defects, respectively, where the first columns present abbreviations and the second columns describe the defects in detail. We decided prior to the experiment to count each defect once for each program.
- **Behavior on test inputs:** To address **RQ2** and **RQ3**, we designed a range of test inputs to expose possible defects. For each test input, we compared the behavior of the two programs from each pair of subjects. These test inputs include *common legal* inputs that test the main functionality of the programs, *rare legal* inputs that still satisfy the input specification but contain corner cases that developers may not handle correctly, and *illegal* inputs that are designed to test the error detection and handling code. Similar to the list of defects, we started with a predefined list of inputs, and included more to trigger new defects that we observed from code review. Appendix A presents all these inputs and their correct outputs.
- **Comparison with failure-oblivious computing:** To address **RQ4**, we implemented a failure-oblivious version of the interpreter for the control group’s language. This interpreter has the same behavior with the original control group interpreter in benign situations and differs in erroneous situations that would originally cause crashes. Specifically, the failure-oblivious interpreter (a) returns value zero for divide-by-zero expressions, out-of-bound array reads, and null array reads and (b) silently ignores out-of-bound array writes and null array writes. For each test input above, we observed the behavior of the control group programs running on the failure-oblivious

Table 2: Possible fatal defects. New defects observed are underlined.

Defect	Description
AWL	Out-of-bound array write when reading input, triggered by input fields that are longer than an input buffer.
AWO	Out-of-bound array write when reading input, triggered by an integer overflow that causes overly small memory allocation.
ARL	Out-of-bound array read during computation, triggered by image dimensions that are too large for an input buffer.
ARO	Out-of-bound array read during computation, triggered by an integer overflow that causes overly small memory allocation.
DS	Division by zero during computation, triggered by a zero scaling factor.
DD	Division by zero when checking integer overflow, triggered by a zero dimension.
NA	Null array access when reading input, triggered by failed memory allocation.
<u>IL</u>	Infinite loop when reading illegal input units.

Table 3: Possible other defects. New defects observed are underlined.

Defect	Description
<u>MP</u>	Memory leak even when processing common legal input units.
MS	Memory leak when skipping input units.
WP	Wrong behavior from producing partial outputs for illegal input units.
WS	Wrong behavior from de-synchronization for at least one input unit after illegal input units.
WM	Wrong behavior from misusing illegal input units and producing outputs for these illegal input units as if they are legal.
<u>WA</u>	Wrong behavior from aborting on illegal input units.

interpreter. For reference, we also analyzed the potential behavior of programs that entered infinite loops if there are tools [14] that help programs (a) escape from infinite loops and (b) continue executing the instructions that follow the escaped loop.

- **Program complexity:** To address **RQ5**, we measured the complexity of the programs in terms of control flow, data manipulation, and total lines of code. These measurements indicate the difficulty of program implementations.
 - **Control-flow complexity:** To estimate the difficulty of error detection, we observe the number of *conditional clauses* in programs. This number contains `if` statements, `assert` statements, logical conjunctions, and logical disjunctions.
 - **Data-manipulation complexity:** To estimate the difficulty of error recovery, we observe the number of *unconditional statements* in programs. This number contains all statements except for `if` and `assert`.
 - **Lines of code:** For reference, we also observe the numbers of lines in the source file, including lines that contain no statements.

Experimental Procedure: The experiment contains a language tutorial and the thumbnail generator task. In the tutorial stage, each subject reads a language manual, runs an

example program, and writes two small programs that may be helpful for implementing the thumbnail generator. These two small writing tasks are important because (a) they interactively *teach* subjects to write and debug with in the experimental language, (b) they *calibrate* two groups to ensure that all subjects from both groups understand the experimental language to similar levels after the tutorials, and (c) they allow us to *detect outliers* based on the subjects’ abilities to write and learn the experimental language.

The specification for the thumbnail generator task explains the program functionality with typical inputs and states that the program should be able to handle arbitrary inputs. For reference, the complete paper materials are presented in Appendix B. The experiments are not limited in duration.

To gain more insight into the developers’ experience, we recorded full screen recordings of the developers as they worked and included a post-experiment questionnaire. The questionnaire asked the subjects for feedback by (a) asking the inspect group to rate the helpfulness of the `inspect` construct, (b) asking all subjects to rate the level of their perceived difficulty [38], and (c) asking for additional comments or clarification.

4.2 Results

Power Analysis: Prior to collecting data, we first estimated the number of subjects we would need to observe statistically significant results. We performed a power analysis [30] using the statistical package R [54]. The power analysis showed that five pairs of subjects would give us 41% statistical power ($1 - \beta = 0.41$)² at a standard 0.05 level ($\alpha = 0.05$), given that we are interested only in large effect sizes [16, 30]. We then performed a pilot experiment to confirm that the effect size for the number of defects—our most important measurement—was likely to be large.

Subjects: Twelve subjects participated. None of them had any prior experience with RIFL. None of them knew about the design or the goals of the study except that it was about language features and program complexity. All subjects volunteered for the study for five dollars’ compensation.

We name each subject with a letter that stands for the group and a number that stands for the pair. Letters “i” and “e” denote the inspect group and the control group, respectively. Among all subjects, ten were matched up into five pairs (1, 2, 4, 5, and 6), based on the similarity of their backgrounds.

Two subjects (e3 and i7) were outliers, because their programs do not produce correct outputs even for common legal inputs, there are no straightforward ways to correct the defects, and the subjects did not learn from solutions to the tutorial problems. Consequently, we removed these

²This power is the probability for us to detect statistical significance when there is true difference between the two groups.

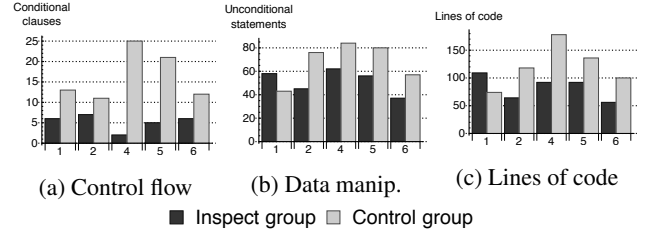


Figure 19: Complexity measurements for user study

outliers from the statistical analysis and did not perform their counterpart experiments (there were no i3 or e7).

We observed that six subjects did not check that their programs generated outputs that matched the specification precisely. Trivial fixes, such as adding the value ‘0’ to the final result, brought the programs into compliance. Two of these fixes (i5 and e6) were applied immediately on the scene after the participants said that they had finished, when the problem was brought to their attention. The other four (i1, e1, e2, and i4) were fixed during our analysis.

Most subjects took comparable time, between one and two hours, to finish the entire experiment. Three subjects (e1, e2, and i7) took between two and three hours. One subject (e3) took more than three hours.

Measurements: Table 4 presents the defects that we found in all the developer programs. Each column represents a thumbnail program by the name of the developer. The rows are: the number of fatal defects (“# fatal”), the list of fatal defects (next eight rows), the number of other defects (“# other”), the list of other defects (next six rows), and the number of all defects (“Total”).

Table 5 presents the behavior of these programs processing the test inputs. Each column represents a thumbnail program. We denote these failure-obliviously executed control group programs with “foc” followed by the pair number. The rows are: the behavior on common legal inputs (the first row), the number of crashes or infinite loops on rare legal inputs (“# crash/loop rare”), the number of wrong outputs on rare legal inputs (“# wrong/explode rare”), the behavior on rare legal inputs (next four rows), the number of crashes or infinite loops on illegal inputs (“# crash/loop illegal”), the number of wrong outputs on illegal inputs (“# wrong/explode illegal”), the behavior on illegal inputs (next 21 rows), the number of crashes or infinite loops on all inputs (“# crash/loop total”), and the number of wrong outputs on all inputs (“# wrong/explode illegal”). We define a wrong output to *explode* if the output size is proportional to the input value, instead of to the input size.

Figure 19 presents the complexity measurements for all the developer programs. The vertical axes in Figures 19a, 19b, and 19c represent control complexity, data complexity, and lines of code, respectively. Each group of two bars represents the two programs from a pair of subjects.

Statistical Analysis: We applied the one-sided Wilcoxon signed-rank tests [77] on all measurements using R [54]. We

Table 5: Behavior of the inspect group programs, original control group programs, and failure-obliviously executed control group programs processing the test inputs. Letters “C”, “L”, “W”, and “E” denote crashing, entering an infinite loop, producing wrong and small outputs, and producing wrong and exploding outputs, respectively. Letter “s” denotes data de-synchronization for at least one subsequent input unit. Letter “a” denotes aborting. The combination “Ls” denotes that the program enters an infinite loop and that the program would de-synchronize after escaping from the infinite loop. Empty cells denote correct behavior. The inspect group is underlined.

Input	Category	<u>i1</u>	e1	foc1	<u>i2</u>	e2	foc2	<u>i4</u>	e4	foc4	<u>i5</u>	e5	foc5	<u>i6</u>	e6	foc6
good	common															
	# crash/loop rare	<u>0</u>	1	0	<u>0</u>	2	0	<u>0</u>	1	0	<u>0</u>	2	0	<u>0</u>	1	0
	# wrong/explode rare	<u>0</u>	0	1	<u>0</u>	0	2	<u>0</u>	0	1	<u>0</u>	0	0	<u>0</u>	0	1
bufovfverylongname	rare					C	W					C				
div0h	rare															
div0w	rare															
heapovf2	rare		C	W		C	W		C	W		C			C	W
	# crash/loop illegal	<u>0</u>	10	0	<u>0</u>	12	4	<u>0</u>	2	0	<u>0</u>	7	0	<u>0</u>	6	0
	# wrong/explode illegal	<u>0</u>	7	16	<u>0</u>	7	14	<u>2</u>	0	1	<u>1</u>	3	8	<u>4</u>	11	17
bufovfint1	illegal		C	E		C	E					C	E		C	Es
bufovfint2	illegal		C	E		C	E					C	E		C	Es
bufovfint3	illegal		C	E		C			C	E		C	E		C	E
bufovfint4	illegal		C	E		C	W					C	E		C	Es
charh	illegal		W	W		Ws	Ws					W	W	<u>W</u>		
charpix1	illegal		W	W		Ws	Ws	<u>W</u>			<u>W</u>			<u>W</u>	Wa	Wa
charpix2	illegal					Ls	Ls								Wa	Wa
chars	illegal		W	W		C	W	<u>W</u>							W	W
chartrail	illegal					Ws	Ws								Ws	Ws
charw1	illegal		W	W		Ws	Ws					W	W	<u>W</u>		
charw2	illegal		C	W		W	W								Ws	Ws
div0s	illegal		C	W		C	W					C	W		C	W
empty	illegal															
heapovf1	illegal		C	E		C	Ls		C			C			C	E
intovf	illegal															
long	illegal		C			C	Ws					C			Ws	Ws
nullint	illegal		W	W		Ws	Ws					Wa	Wa	<u>W</u>	Ws	Ws
short1	illegal		W	W		Ls	Ls								W	W
short2	illegal		C	W		Ws	Ws								Ws	Ws
short3	illegal		W	W		Ls	Ls								W	W
short4	illegal		C	W		C	Ws								Ws	Ws
	# crash/loop total	<u>0</u>	11	0	<u>0</u>	14	4	<u>0</u>	3	0	<u>0</u>	9	0	<u>0</u>	7	0
	# wrong/explode total	<u>0</u>	7	17	<u>0</u>	7	16	<u>2</u>	0	2	<u>1</u>	3	8	<u>4</u>	11	18

assume that the differences are comparable across pairs [69]. We observed statistical significance to reject null hypotheses where the p-values are less than the standard significance level, 0.05.

- **Defects, RQ1:** According to the results of the tests, the inspect group has significantly fewer defects (p-value = 0.029) and fewer fatal defects (p-value = 0.029) than the control group. The inspect group also tends to have fewer non-fatal defects than the control group (p-value = 0.068).
- **Survivals, RQ2:** The inspect group crashes or enters infinite loops on significantly fewer occasions than the control group when processing rare legal inputs (p-value = 0.027), illegal inputs (p-value = 0.031), and all inputs (p-value = 0.031).
- **Wrong outputs, RQ3:** The inspect group tends to produce fewer wrong outputs than the original control group when processing illegal inputs (p-value = 0.064).
- **Wrong outputs with failure-oblivious computing, RQ4:** The inspect group produces fewer wrong outputs than the failure-obliviously executed control group programs when processing rare inputs (p-value = 0.044). The inspect group tends to produce fewer wrong outputs than the failure-oblivious control group when processing illegal inputs (p-value = 0.063) and all inputs (p-value = 0.050).
- **Program complexity, RQ5:** The inspect group programs have significantly fewer conditional clauses (p-value = 0.031) than the control group programs do. The inspect group programs also tend to have fewer unconditional statements (p-value = 0.063) and fewer lines of code (p-value = 0.052).

Our overall conclusion is that these results support the hypothesis that the RIFL filtered iterators can enable a range of developers to produce safe and robust programs with significantly fewer defects than comparable developers using standard language constructs. We also note that the numerous defects—including defects corresponding to typical secu-

Table 4: Defects in developer programs. Letter “X” denotes the existence of a defect. The inspect group is underlined.

Defect	<u>i1</u>	e1	<u>i2</u>	e2	<u>i4</u>	e4	<u>i5</u>	e5	<u>i6</u>	e6
# fatal	<u>0</u>	4	<u>0</u>	5	<u>0</u>	2	<u>0</u>	4	<u>0</u>	3
AWL		X		X				X		
AWO										
ARL		X								
ARO				X		X		X		X
DS		X		X				X		X
DD										
NA		X		X		X		X		X
IL				X						
# other	<u>1</u>	2	<u>0</u>	4	<u>1</u>	0	<u>2</u>	4	<u>2</u>	5
MP		X					<u>X</u>	X	<u>X</u>	X
MS	<u>X</u>			X				X		
WP				X						X
WS				X						X
WM		X		X	<u>X</u>		<u>X</u>	X	<u>X</u>	X
WA								X		X
Total	<u>1</u>	6	<u>0</u>	9	<u>1</u>	2	<u>2</u>	8	<u>2</u>	8

rity vulnerabilities—present in the control group programs are consistent with the defects observed in input-processing code more broadly. Filtered iterators eliminate the vast majority of these defects.

4.3 Discussion

We attribute the statistically significant results from only five pairs of subjects to the fact that the difference between the inspect group and the control group is very large.

Program Robustness: Defects, survivals, and wrong outputs are three measures of program robustness. RIFL’s filtered iterators enhance input-parsing programs’ robustness by reducing defects, increasing survivals, and reducing wrong outputs. We attribute these improvements to the fact that filtered iterators automatically filter out bad input units and allow programs to continue execution from an earlier, consistent state.

Program Complexity: RIFL’s filtered iterators reduce the complexity of input-parsing programs by significantly reducing the number of conditional clauses. For the other two aspects—unconditional statements and lines of code—the complexity measurements were reduced somewhat, though not statistically significant³. We attribute these improvements to the fact that the semantics of filtered iterators ensure the atomicity of input units.

Participants’ Feedback: Two subjects from the inspect group (i1 and i2) responded that the `inspect` construct was very helpful for implementation. One of them (i2) reported verbally that `inspect` frees him/her of the needs to consider many corner cases. The other (i1) reported verbally that, without a good integrated development environ-

³From our manual examination of the developers’ programs, we attribute this lack of significance to the noise caused by various approaches to implementing the same functionality.

ment (IDE)⁴, he/she had to debug manually by inserting `print` and `continue` statements. Two subjects (i4 and i5) responded that `inspect` was somewhat helpful, but also makes debugging hard without a good IDE, because it makes some unintentional errors silent. One subject (i7) responded that `inspect` was somewhat useless during development, because he/she would like his/her programs to “blow up and scream at” him/her when something is wrong. The last inspect group subject (i6) responded that `inspect` was useless, and did not clarify further on this point. Despite this comment, we note that, using the `inspect` construct, this subject produced a program with significantly fewer errors than his/her counterpart (e6).

This developer feedback highlights a difference between software that is under development and software that is in production. If deployed during development, mechanisms that help software tolerate errors may inhibit the development of quality software by triggering a bystander effect [21, 42, 57] that demotivates developers to improve the software. Understanding how this phenomenon could affect RIFL developers requires some sophistication. One of the goals of RIFL is to free developers from the need to produce code that handles corner-case input units that the application should discard. Ideally, RIFL developers would not even have to mentally conceptualize or consider such cases. In this situation, the RIFL mechanisms constitute a beneficial bystander that enhances developer productivity by reducing the developer’s mental load.

The potential drawback comes when the developer makes unintentional errors when processing input units that the application should handle properly. One way to navigate this dichotomy of inputs is to develop software with a more sophisticated testing approach—classifying test inputs into (a) tests that the application should fully process and (b) tests containing input units that the application should discard. This categorization enables RIFL developers to highlight the inputs that the application should fully process by configuring the RIFL runtime to raise visible errors for these inputs, instead of silently discarding input units that trigger errors. This enhancement would properly motivate developers to produce code that correctly implements the basic functionality of the application. This approach would both (a) preserve the benefits of the RIFL mechanisms that implicitly discard input units that the program cannot correctly process and (b) provide the visible error feedback that helps developers find and eliminate errors for which they are responsible. We note that there is a conceptual similarity to just in time manufacturing approaches, which are designed to drive the development of effective manufacturing processes by making errors immediately visible.

⁴Unlike the complete RIFL interpreter, the interpreters developed for the controlled experiment produced only final outputs for both groups. There were no error logs that could help developers debug programs when `inspect` loops discard bad input units.

5. Other Input File Formats

We also investigated the use of RIFL for the following input file formats. Binary formats include PCAP/DNS, RGIF, PNG, and ZIP. Text formats include JSON, OBJ, and CSV. More detail about these benchmarks, including source code, are presented in Appendix C.

- **PCAP/DNS:** A network traffic capture [6] format, PCAP [23], stores network packets. The PCAP/DNS benchmark implementations analyze Domain Name System (DNS) packets from PCAP files, printing the Internet Protocol (IP) addresses, the DNS identification number, and the DNS questions and answers.
- **RGIF:** We adapt the Graphics Interchange Format (GIF) [3], which stores animated images, to become more resilient to malformed image components. We call this new format RGIF. It differs from GIF by adding two bytes in front of each image to describe the length of all blocks for the image. The RGIF benchmark implementations convert an RGIF file to the GIF format.
- **Portable Network Graphics (PNG):** The PNG format [11] stores images. The PNG benchmark implementations concatenate all image data in an PNG file.
- **ZIP:** The ZIP format [52] stores archived user files. The ZIP benchmark implementations output the name and the archived contents for all user files.
- **JavaScript Object Notation (JSON):** The JSON format [12] describes an object. The JSON benchmark implementations copy inputs to outputs, discarding any bad components.
- **OBJ:** OBJ [4] files store three-dimensional (3D) object geometry. The OBJ benchmark implementations copy inputs to outputs, discarding any bad components.
- **Comma Separated Values (CSV):** CSV [63] files store tables. The CSV benchmark implementations copy inputs to outputs, discarding bad components.

5.1 Methodology

We implemented four versions of each program: (a) *Full RIFL*: this version uses inspect loops to automatically extract input units, to detect bad units, and to recover from bad units, (b) *Explicit Check*: this version uses inspect loops with exhaustive assertions to explicitly identify bad input units that the RIFL implementation automatically discards on these assertion failures, (c) *Explicit Recovery*: this version uses RIFL iterators but with fully explicit error handling so the RIFL error detection and recovery mechanisms never deploy, and (d) *Conventional*: this version uses conventional language constructs.

All versions of the same benchmark program have the same functionality and produce the same outputs for most inputs. In practice, it is sometimes inappropriate to require exactly the same outputs. For example, when a program

rejects an input file entirely because the input significantly differs from the specification, the full-RIFL and explicit-check versions may use assertions outside inspect loops, while it may be more natural for the other two versions to use `exit` statements that terminate programs with error codes and partial outputs.

We compared all versions of each program in terms of control complexity, data complexity, and lines of code. We also analyzed the differences between the source code for all versions of the same programs and classified the differences into importance categories.

5.2 Results

Figure 20 presents the measurements for all versions of all benchmark programs. The vertical axes in Figures 20a, 20b, and 20c represent control complexity, data complexity, and lines of code, respectively. Each group of four bars represents the four versions of a program.

Tables 6, 7, and 8 present the average percentage decrease in control complexity, data complexity, and lines of code from each version. The columns are averages for binary formats (Binary), averages for text formats (Text), and averages for all seven benchmarks (Overall). The rows are average percentage decreases in complexity: from conventional to explicit-recovery versions (Iterator), from explicit-recovery to explicit-check versions (Implicit recovery), from explicit-check to full-RIFL versions (Implicit detection), and from conventional to full-RIFL versions (Overall). Filtered iterators reduce the numbers of conditional clauses and unconditional statements from conventional versions by an average of 58.5% and 33.4%, respectively. Overall, filtered iterators reduce the number of lines of code by an average of 41.7%.

Table 9 presents our perception of the categories of the error-handling code that the full-RIFL versions eliminate from the conventional versions. Each row corresponds to a benchmark program. Columns two through four correspond to importance categories: preventing crashes (Vital), preventing input misinterpretation (Integrity), and part of common engineering practice (Common). The last two columns correspond to the total numbers eliminated in all three categories (Total) and the total numbers present in the conventional versions (Size), respectively.

5.3 Discussion

We attribute the improvements of eliminated error-handling code to the fact that the full-RIFL versions need only code that handles common cases. Specifically: (a) Iterators can help eliminate the code that identifies the boundaries between input units and prevents de-synchronization in case of bad input units. (b) Implicit error recovery can help eliminate the code that maintains program state and avoids partial outputs when discarding bad input units. (c) Implicit error detection can help eliminate the conditionals that prevent program crashes by checking corner cases that developers may not consider. The omission of these conditionals in con-

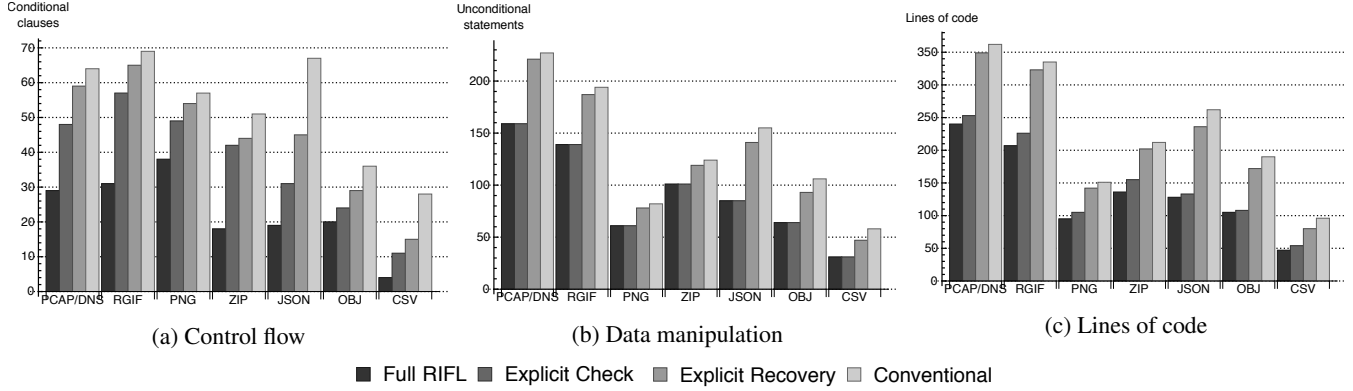


Figure 20: Complexity measurements for benchmarks

Table 6: Average decrease in control flow

Feature	Binary	Text	Overall
Iterator	8.1%	32.9%	18.8%
Implicit recovery	11.2%	25.0%	17.1%
Implicit detection	41.2%	39.7%	40.5%
Overall	51.9%	67.3%	58.5%

Table 7: Average decrease in data manipulation

Feature	Binary	Text	Overall
Iterator	3.8%	13.4%	7.9%
Implicit recovery	22.7%	35.0%	27.9%
Implicit detection	0.0%	0.0%	0.0%
Overall	25.6%	43.8%	33.4%

Table 8: Average decrease in lines of code

Feature	Binary	Text	Overall
Iterator	4.5%	12.0%	7.7%
Implicit recovery	26.7%	37.8%	31.5%
Implicit detection	8.8%	6.5%	7.8%
Overall	36.2%	49.0%	41.7%

Table 9: Error-handling code totals for benchmarks. Each pair of numbers separated by a slash “/” are the numbers of conditional clauses and of unconditional statements.

Benchmark	Vital	Integrity	Common	Total	Size
PCAP/DNS	8 / 9	26 / 58	1 / 1	35 / 68	64 / 227
RGIF	10 / 5	27 / 50	1 / 0	38 / 55	69 / 194
PNG	4 / 3	13 / 18	2 / 0	19 / 21	57 / 82
ZIP	7 / 1	16 / 19	10 / 3	33 / 23	51 / 124
JSON	13 / 4	32 / 62	3 / 4	48 / 70	67 / 155
OBJ	5 / 3	10 / 38	1 / 1	16 / 42	36 / 106
CSV	4 / 1	18 / 25	2 / 1	24 / 27	28 / 58

ventional versions would, therefore, typically lead to errors when processing the inputs with these corner cases.

6. Related Work

The notion of filtered iterators combines filters, iterators and atomic transactions with input units. Filtered iterators treat inputs as collections of input units, iterate over the units, use the programs to filter out bad units, and atomically update program state for each unit. A filter function extracts a subset from a collection so that each element satisfies a given predicate. Filters date back to the `remove-if` function in Common Lisp [70] and the `select` message in Smalltalk [32]. An iterator is a generalization of loops over collections, which separates the action performed on each object from the selection of the objects. The concept of iterators was originally proposed in CLU [44] as a control abstraction. RIFL abstracts the input as a structured collection of input units. Many modern languages [2, 5] support iterators with explicit filtering predicates. RIFL, in contrast, uses the execution of the program itself as an implicit filter. The result is automatic detection and recovery from a range of errors. Loop perforation [67] drops loop iterations from the computation. RIFL drops input units from the inputs. A transaction is a group of actions with ACID properties: atomicity, consistency, isolation and durability. Transactions ensure the consistency in spite of concurrency and failures for database systems [31, 35, 36] and for distributed systems [43]. Transactions are used as an alternative abstraction to explicit synchronization [45]: transactional memory [39, 64, 71] implementations simplify the management of concurrent data structures. RIFL uses transactions in filtered iterators to enforce the atomicity of input units.

Researchers have proposed ways to recover software from errors. Many of them are external to the language definition. Transactional recovery techniques such as backward recovery [15] and forward recovery [40] recover programs from transient errors. Rx [53] rolls back and replays programs in new configurations to survive failures. These techniques are unlikely to solve deterministic errors. Filtered

iterators capture all detectable errors and recover from them by discarding bad inputs and restarting loop iterations.

Input filtering systems [13, 17, 18, 47, 73, 75] generate vulnerability signatures from known attacks and drop malicious inputs accordingly. These techniques are usually unsound—they cannot block all attacks. Input rectification [46, 58] prevents program failures by modifying bad inputs to good ones using prior knowledge about benign inputs. The RIFL runtime dynamically captures and recovers from all detectable vulnerabilities with neither false positives nor false negatives. RIFL also uses programs themselves as filters, without external knowledge.

Failure-oblivious techniques [48, 57] purposefully change the program semantics to survive inputs that the program would otherwise be unable to process. Error virtualization [65, 66] recovers program execution by turning function executions into transactions and mapping faults into return values used by the application code. These techniques aim to change the semantics of existing programs to improve robustness, but with at best uncertain impacts on the semantics of the program. RIFL, in contrast, provides semantics that have no anomalous effects from bad inputs.

Researchers have also proposed language-based techniques to error recovery. Recovery blocks [7] and N-version programming [8] tolerate software faults using multiple implementations of the same component. Exception handling [19, 33] improves program structures by separating common-case and error-handling code. This structure requires developers to anticipate the exceptional events and maintain program state accordingly. In contrast to these methodologies, RIFL aims at eliminating the need for error-handling code. Bristlecone [24, 26, 27] ensures error-free execution using decoupled transactional tasks according to high-level task specifications. RIFL and Bristlecone both help programs survive by discarding computation from the conceptual level. RIFL’s filtered iterators allow program structures to be closer to existing programs than Bristlecone’s task descriptions would.

7. Conclusion

Input validation defects are a common and serious source of software errors and security vulnerabilities. By dividing inputs into input units and atomically discarding input units that trigger errors, RIFL promotes the development of reliable and robust software systems. Statistically significant results from a developer study demonstrate the empirical benefits that RIFL can provide.

More generally, RIFL embodies a different approach to programming language design. Instead of operating from abstract philosophical principles such as simplicity, orthogonality, or elegance, RIFL targets a specific problem that has emerged through experience with existing languages over time, provides a construct designed to emulate the effect of observed developer fixes, and validates its approach using

empirical techniques rather than abstract philosophical arguments. As the field matures and acquires the experience required to more accurately identify the important issues that actually occur in practice, we expect this more empirical approach to comprise one effective approach to programming language design.

A. Inputs for Testing Programs from the Developer Study

A.1 Common Legal Inputs

- Input “good”:

```
Img1_2_2_2_1234
Img2_2_4_4_1234567890123456
Img3_2_1_2_12
Img4_3_3_4_123456789012
Img5_5_5_10_
0123456789012345678901234567890123456789012345678901234567890
```

Correct output:

```
Img1_2
Img2_3543
Img3_
Img4_3
Img5_27
```

A.2 Rare Legal Inputs

- Input “bufovfverylongname”:

```
Buf0vfVeryLongName_2_2_2_1234
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

or

```
Buf0vfVeryLongName_2
Img5_2
```

- Input “div0h”:

```
Div0H_2_0_2
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

or

```
Div0H_
Img5_2
```

- Input “div0w”:

```
Div0W_2_2_0
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

or

Div0W_
Img5_2

- **Input “heapovf2”:** The first line contains “HeapOvf2_1_200_1000_” followed by 20000 repetitions of “1234567890”. The second line contains “Img5_2_2_2_1234”. Correct output:

Img5_2

or

The first line contains “HeapOvf2_” followed by 20000 repetitions of “1234567890”. The second line contains “Img5_2”.

A.3 Illegal Inputs

- **Input “bufovfint1”:**

BufOvfInt1_2_16_268435457_16_12345678901234567890
Img5_2_2_2_1234

Correct output:

Img5_2

- **Input “bufovfint2”:**

BufOvfInt2_2_2_268435457_16_12345678901234567890
Img5_2_2_2_1234

Correct output:

Img5_2

- **Input “bufovfint3”:**

BufOvfInt3_1_268435457_16_1234567890123456
Img5_2_2_2_1234

Correct output:

Img5_2

or

BufOvfInt3_1234567890123456
Img5_2

- **Input “bufovfint4”:**

BufOvfInt4_1_268435457_16_12345678901234567890
Img5_2_2_2_1234

Correct output:

Img5_2

- **Input “charh”:**

CharH_2_2_2_1234
Img5_2_2_2_1234

Correct output:

Img5_2

or

CharH_2
Img5_2

- **Input “charpix1”:**

CharPix1_2_2_2_12a4
Img5_2_2_2_1234

Correct output:

Img5_2

- **Input “charpix2”:**

CharPix2_3_3_4_123a567b901c
Img5_2_2_2_1234

Correct output:

Img5_2

or

CharPix2_3
Img5_2

- **Input “chars”:**

CharS_b_2_2_1234
Img5_2_2_2_1234

Correct output:

Img5_2

- **Input “chartrail”:**

CharTrail_2_2_2_1234b
Img5_2_2_2_1234

Correct output:

Img5_2

or

CharTrail_2
Img5_2

- **Input “charw1”:**

CharW1_2_2_2_1234
Img5_2_2_2_1234

Correct output:

Img5_2

or

CharW1_2
Img5_2

- **Input “charw2”:**

CharW2_2_2a_2_1234
Img5_2_2_2_1234

Correct output:

Img5_2

- **Input “div0s”:**

Div0S_0_2_2_1234
Img5_2_2_2_1234

Correct output:

```
Img5_2
```

• **Input “empty”:**

```
_2_2_2_1234  
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

or

```
_2  
Img5_2
```

• **Input “heapovf1”:**

```
HeapOvf1_2_200_1000_1234  
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

• **Input “intovf”:**

```
IntOvf_2_2_4294967298_1234  
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

or

```
IntOvf_2  
Img5_2
```

• **Input “long”:** The first line contains “Long_2_2_2_” followed by eleven repetitions of “1234567890”. The second line contains “Img5_2_2_2_1234”. Correct output:

```
Img5_2
```

or

```
Long_2  
Img5_2
```

• **Input “nullint”:**

```
NullInt_2_2_4294967295_1234  
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

• **Input “short1”:**

```
Short1_2  
2_2_1234  
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

• **Input “short2”:**

```
Short2_2_2_2_  
123  
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

• **Input “short3”:**

```
Short3_2_4_4_  
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

• **Input “short4”:**

```
Short4  
Img5_2_2_2_1234
```

Correct output:

```
Img5_2
```

B. Paper Materials for the Developer Study

B.1 Consent Form

CONSENT TO PARTICIPATE IN EXPERIMENT

Title of the Study: Language Features and Program Complexity

You have been asked to participate in a research study conducted by Jiasi Shen from the Department of Electrical Engineering and Computer Science (EECS) at the Massachusetts Institute of Technology (M.I.T.). The purpose of the study is to investigate how the features of a programming language affect the difficulty of reading and writing programs. The results of this study will be published as a report. You were selected as a possible participant in this study because you are an experienced software developer. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- This experiment is voluntary. You have the right not to answer any question, and to stop the experiment at any time or for any reason. We expect that the experiment will take 30-60 minutes.
- You will be compensated \$5 for this experiment.
- Your name will remain confidential. Unless you give us permission to quote you in any publications that may result from this research, the information you tell us will be confidential.
- You will be asked to read and write programs inside a virtual environment. For analyzing purposes, we will record the *visual* information that this virtual environment displays as you perform the tasks. The information we learn from these recordings will be made anonymous in our reports.

This project will be completed by July 2016.

(Please check all that apply)

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

I give permission for direct quotes from this experiment to be included in publications resulting from this study.

Name of Subject _____

Signature of Subject _____ Date _____

Signature of Investigator _____ Date _____

Please contact Jiasi Shen (jiasi@csail.mit.edu) with any questions or concerns.

If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143b, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253-6787.

Amendment Approved on 03-NOV-2015

Exemption Granted 17-AUG-2015

B.2 Inspect Group Instructions

Instructions

You are going to write three programs using a new programming language. Please follow the instructions below to confirm your eligibility, setup the virtual machine, learn the language, complete the writing tasks, complete surveys regarding your experience, and submit your data.

1 Eligibility

In the **past five years**, you have _____ years' experience using imperative languages _____ (such as C/C++, Java, or Python).

2 Environmental setup

1. Launch the virtual machine by opening the file “LanguageFeaturesVM.vmwarevm” with VMware Fusion.
2. Adjust the VMware window to your screen, so that you can see both the lower-left corner with a trash-can icon and the upper-right corner with a gadget icon.
3. Launch the screen recorder by clicking the blue monitor icon on the left. A window titled “vokoscreen 1.9.0” should appear.¹
4. Click “Start” in the vokoscreen window. The vokoscreen window should minimize automatically, and there should be a small white triangle to the left of the blue monitor icon that you have previously clicked.
5. Launch a terminal by clicking the black rectangle icon on the left. A terminal window titled “default@ubuntu: ~\Desktop” should appear.

¹For analyzing purposes, we record the screen in the virtual machine as you perform tasks in this experiment. We have configured vokoscreen to record the full screen, without audio, capturing 25 frames per second, encoding in the x264 format, storing into an avi file, and including mouse cursor movements. Feel free to double check these configurations and ask the experimenter if you have any questions.

3 Language tutorial

The language used in this experiment is similar to many other imperative languages such as C, but includes an additional looping construct: `inspect`.

1. Learn about `inspect` loops by reading *The inspect Construct*.
2. Learn about the rest of the language by reading the *Language Manual*.
3. **Double-click** the file “prog0.stu” on the desktop. An editor window titled “prog0.stu (~\Desktop) – gedit” should appear. This file contains an example program that counts the number of characters on each line of the file “input0.txt”.
4. Run this example program by entering

```
run prog0.stu
```

in the terminal. You should see

```
[Program return value]: 0.  
\5  
\3  
\0
```

in the same terminal window. The first line presents the value returned from the program’s `main` function. Then follows the outputs from `print` statements. The strings “\5”, “\3”, and “\0” indicate that there are 5, 3, and 0 characters on the first, the third, and the fourth lines, respectively. The newline character between “\5” and “\3” indicates that there are 10 characters on the second line, since the number 10 corresponds to the newline character ‘\n’ in ASCII encoding.

5. Feel free to edit files “prog0.stu” and “input0.txt” and run the program again.

4 Writing tasks

There are three writing tasks. The first two tasks should help you complete the third task. Please complete them in order, and fill in the time that you start and finish each task.

4.1 Summing Matrix Elements

Started reading at _____ : _____ : _____

Your task is to fill in a program that sums up some elements in a 3×3 matrix, $\begin{pmatrix} 0 & 1 & 2 \\ 3 & 4 & 5 \\ 6 & 7 & 8 \end{pmatrix}$. An input file specifies the elements to include. In this task and only in this task, you may assume that the input file is correct.

- **Input format:** Four ASCII-encoded digits:
 - i_0 , the starting row index.
 - j_0 , the starting column index.
 - h , the height.
 - w , the width.

These numbers satisfy that $0 \leq i_0 < i_0 + h \leq 3$ and that $0 \leq j_0 < j_0 + w \leq 3$. Row and column indices start from 0.

- **Output format:** A byte that contains the sum of the elements between rows $i_0 \dots (i_0 + h - 1)$ and columns $j_0 \dots (j_0 + w - 1)$.

Figure 1 presents sample input and output. The program sums up all elements in the last two columns of the matrix: $1 + 2 + 4 + 5 + 7 + 8 = 27$. The `print` statement displays 27 as “\27”.

0132

(a) Sample input

\27

(b) Sample output

Figure 1: Sample input and output

Finished reading at _____ : _____ : _____

Please implement this program in file “prog1.stu”, **save** the file, and run the program by entering “`run prog1.stu`” in the terminal. If there is no response, press Ctrl+C in the terminal and check if your program contains an infinite loop.

File “input1.txt” contains the sample input. Please test your program as you normally would.

Finished implementing at _____ : _____ : _____

After your implementation, please read the **sample solution** for this problem.

4.2 Converting ASCII Integers

Started reading at _____ : _____ : _____

Your task is to write a program that parses an integer preceding the first space character on each line of a file. Your program should be able to handle arbitrary inputs by skipping malformed lines.

- **Input format:** Each line starts with an ASCII-encoded, variable-length integer followed by a space character.
- **Output format:** Each output byte has the value of the leading integer from each input line.

Figure 2 presents sample input and output. Table 1 explains the sample output.

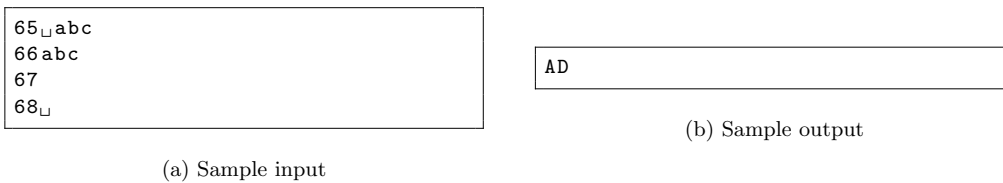


Figure 2: Sample input and output

Table 1: Explanation for sample output

Input line	Output byte	Explanation
1	65	“ <code>print(65);</code> ” displays ‘A’
2	(skipped)	unexpected character ‘a’
3	(skipped)	the trailing space character is missing
4	68	“ <code>print(68);</code> ” displays ‘D’

Finished reading at _____ : _____ : _____

Please implement this program in file “prog2.stu”, **save** the file, and run the program by entering “`run prog2.stu`” in the terminal. If there is no response, press Ctrl+C in the terminal and check if your program contains an infinite loop.

File “input2.txt” contains the sample input. Please test your program as you normally would.

Finished implementing at _____ : _____ : _____

After your implementation, please read the **sample solution** for this problem.

4.3 Image Thumbnail Generator

Started reading at _____ : _____ : _____

Your task is to write a program that generates thumbnails for multiple bitmap images in a file. Your program should be able to handle arbitrary inputs by skipping malformed images.

Image thumbnails are small images that capture the overall shape of large images. For example, a thumbnail for Figure 3 is shown in Figure 4.

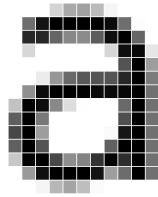


Figure 3: Magnified original image

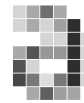


Figure 4: Magnified thumbnail

You are going to use the following algorithm that averages neighboring pixel values. Given a scaling factor s , the thumbnail for an image of height h and width w has height $\lfloor h/s \rfloor$ and width $\lfloor w/s \rfloor$. The value of the pixel in row i and column j of the thumbnail is the floor average of the values of all pixels in the s^2 square area between rows $i \cdot s \dots (i \cdot s + s - 1)$ and columns $j \cdot s \dots (j \cdot s + s - 1)$ of the original image.

- **Input format:** Each line describes an original image. Each line contains the following contents separated by a single space character:
 - An image name, which is a string of 1–10 characters long.
 - An ASCII-encoded variable-length integer, s , that represents the scaling factor.
 - An ASCII-encoded variable-length integer, h , that represents the original image height.
 - An ASCII-encoded variable-length integer, w , that represents the original image width.
 - $h \cdot w$ consecutive digits that each represents a pixel value. The pixels are ordered as follows: inside each row, pixels are ordered from left to right; the rows are each grouped together and ordered from top to bottom. Each pixel has one of ten possible values: '0'... '9'.
- **Output format:** The output contains lines that each describes a thumbnail. Each line contains the following contents separated by a single space character:
 - The image name.
 - $\lfloor h/s \rfloor \cdot \lfloor w/s \rfloor$ consecutive digits that each represents a pixel value.

Figure 5 presents sample input and output. Table 2 explains the sample output.

```

Img1_2_2_2_1234
Img2_2_4_4_1234567890123456
Img3_2_1_2_12
Img4_3_3_4_123456789012

```

(a) Sample input

```

Img1_2
Img2_3543
Img3_
Img4_3

```

(b) Sample output

Figure 5: Sample input and output

Table 2: Explanation for sample output

Name	Original	Thumbnail	Explanation
Img1	<pre> 1 2 3 4 </pre>	2	With $s = 2$, the thumbnail for Img1 has height $\lfloor 2/2 \rfloor = 1$ and width $\lfloor 2/2 \rfloor = 1$. The single pixel has the value of $\lfloor (1 + 2 + 3 + 4)/4 \rfloor = \lfloor 10/4 \rfloor = 2$.
Img2	<pre> 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 </pre>	<pre> 3 5 4 3 </pre>	With $s = 2$, the thumbnail for Img2 has height $\lfloor 4/2 \rfloor = 2$ and width $\lfloor 4/2 \rfloor = 2$. The top-left pixel in the thumbnail has the value of $\lfloor (1 + 2 + 5 + 6)/4 \rfloor = 3$. The top-right pixel in the thumbnail has the value of $\lfloor (3 + 4 + 7 + 8)/4 \rfloor = 5$. The bottom-left pixel in the thumbnail has the value of $\lfloor (9 + 0 + 3 + 4)/4 \rfloor = 4$. The bottom-right pixel in the thumbnail has the value of $\lfloor (1 + 2 + 5 + 6)/4 \rfloor = 3$.
Img3	<pre> 1 2 </pre>	(empty)	With $s = 2$, the thumbnail for Img3 has height $\lfloor 1/2 \rfloor = 0$. This height indicates that the thumbnail image is empty.
Img4	<pre> 1 2 3 4 5 6 7 8 9 0 1 2 </pre>	3	With $s = 3$, the thumbnail for Img4 has height $\lfloor 3/3 \rfloor = 1$ and width $\lfloor 4/3 \rfloor = 1$. The single pixel has the value of $\lfloor (1 + 2 + 3 + 5 + 6 + 7 + 9 + 0 + 1)/9 \rfloor = \lfloor 34/9 \rfloor = 3$.

Finished reading at _____ : _____ : _____

Please implement this program in file “prog3.stu”, **save** the file, and run the program by entering “run prog3.stu” in the terminal. If there is no response, press Ctrl+C in the terminal and check if your program contains an infinite loop.

File “input3.txt” contains the sample input. Please test your program as you normally would.

Finished implementing at _____ : _____ : _____

5 Survey

5.1 Summing Matrix Elements

Mental Demand. How mentally demanding was task 1?

Please rate from 0 (very low) to 10 (very high).

Temporal Demand. How hurried or rushed was the pace of task 1?

Please rate from 0 (very low) to 10 (very high).

Performance. How successful were you in accomplishing task 1?

Please rate from 0 (failure) to 10 (perfect).

Frustration. How insecure, discouraged, irritated, stressed, and annoyed were you?

Please rate from 0 (very low) to 10 (very high).

How many times did you cheat? Where did you cheat?

Don't worry, there is no punishment for cheating.

Any other comments or clarification?

5.2 Converting ASCII Integers

Did the inspect construct help you with task 2?

Please circle: very helpful somewhat helpful neutral somewhat useless very useless

Mental Demand. How mentally demanding was task 2?

Please rate from 0 (very low) to 10 (very high).

Temporal Demand. How hurried or rushed was the pace of task 2?

Please rate from 0 (very low) to 10 (very high).

Performance. How successful were you in accomplishing task 2?

Please rate from 0 (failure) to 10 (perfect).

Frustration. How insecure, discouraged, irritated, stressed, and annoyed were you?

Please rate from 0 (very low) to 10 (very high).

How many times did you cheat? Where did you cheat?

Don't worry, there is no punishment for cheating.

Any other comments or clarification?

5.3 Image Thumbnail Generator

Did the inspect construct help you with task 3?

Please circle: very helpful somewhat helpful neutral somewhat useless very useless

Mental Demand. How mentally demanding was task 3?

Please rate from 0 (very low) to 10 (very high).

Temporal Demand. How hurried or rushed was the pace of task 3?

Please rate from 0 (very low) to 10 (very high).

Performance. How successful were you in accomplishing task 3?

Please rate from 0 (failure) to 10 (perfect).

Frustration. How insecure, discouraged, irritated, stressed, and annoyed were you?

Please rate from 0 (very low) to 10 (very high).

Any other comments or clarification?

6 Submission

1. Stop the screen recorder by clicking the blue monitor icon on the left and then clicking “Stop” in the window named “vokoscreen 1.9.0”.
2. Shut down the virtual machine by clicking the gadget icon on the top-right corner, the “Shut Down...” option at the bottom of the drop-down menu, and the “Shut Down” icon on the right. DO NOT shut down from the VMware menu.
3. Send your updated file “LanguageFeaturesVM.vmwarevm” back to the experimenter.
4. Turn in this document.

B.3 Inspect Group Tutorials, Part I—The inspect Construct

The inspect Construct

An `inspect` loop is an iterator that automatically avoids errors. The syntax is as follows.

```
inspect (input_file, delimiter) {  
    // Execute these statements on each input unit that allows successful execution.  
    // These statements may contain function calls.  
}
```

To illustrate the usage, we first present a small example. Say that we would like to collect the leading letters from all lines in a document. We would like to process the lines that start with alphabetic letters and to ignore the lines that start with other characters. Figure 1 presents sample input and output. Figure 2 compares two solutions, where Figure 2a uses traditional constructs and Figure 2b uses the `inspect` construct.

The program in Figure 2b works as follows. It first associates `f` to an input file named “data”. The file consists of smaller input units, specifically, lines. The program starts execution from the `main` function, where an `inspect` loop iterates over the lines in file `f` until reaching the end of the file. For each line, the `inspect` loop automatically determines whether or not to execute the loop body based on whether or not the execution would succeed. Specifically,

- If a line starts with an alphabetic letter, the `inspect` loop executes the body which prints this leading letter.
- If a line does not start with an alphabetic letter, the `inspect` loop does not execute the body, so that there is no assertion failure.

In general, `inspect` loops iterate over delimited input units, skipping the units that would trigger errors. Consequently, each input unit is either successfully processed or completely ignored. The semantics use the following two criteria.

- **Delimiters:** A specified delimiter decomposes the input into smaller input units. An input unit is the contents between two delimiters. Each time the `inspect` body starts, a fresh input unit is available to be read.
- **Errors:** The `inspect` loop automatically skips the input units that would trigger errors if processed. Errors include assertion violations, arithmetic errors, array-access errors, file-access errors, attempts to read beyond input units, and resource exhaustion.

For completeness, please refer to other language constructs in a separate manual.

```
Hello,  
world  
!
```

(a) Sample input

```
Hw
```

(b) Sample output

Figure 1: Sample input and output

```
f = open("data");  
main {  
  while (!end(f)) {  
    x = read(f);  
    if ((x>='a' && x<='z') || (x>='A' && x<='Z')) {  
      print(x);  
    }  
    while (!end(f) && x!='\n') {  
      x = read(f);  
    }  
  }  
  return 0;  
}
```

(a) Traditional solution

```
f = open("data");  
main {  
  inspect (f, '\n') {  
    x = read(f);  
    assert((x>='a' && x<='z') || (x>='A' && x<='Z'));  
    print(x);  
  }  
  return 0;  
}
```

(b) inspect solution

Figure 2: Solutions

B.4 Inspect Group Tutorials, Part II—Other Language Constructs

Language Manual

This manual presents a subset of a programming language that contains simplified C constructs. For quick references, Tables 1, 2, and 3 list the sections that explain basic syntax, data operations, and control structures, respectively.

Table 1: Basic syntax

Keyword	Description	Section
	formatting	1.1
	comments	1.2
	variables	1.3
print	output an integer value	1.4
assert	assert an expression to be “true” (nonzero)	1.5

Table 2: Data operations

Keyword	Description	Section
	integer expressions	2.1
	array accesses	2.2
malloc	allocate memory for an array	2.2
free	deallocate memory from an array	2.2
open	open an input file	2.3
read	read a byte from an input file	2.3
end	test the end of the current input unit or input file	2.3
seek	update the input offset	2.3
pos	return current input offset	2.3

Table 3: Control structures

Keyword	Description	Section
if/if-else	conditional statements	3.1
while	loops	3.2
break	exit the current loop	3.2
continue	skip the current loop iteration	3.2
main	define the main function where a program starts	3.3
func	define a user function	3.4
return	return a value for a function	3.4

1 Basic syntax

1.1 Formatting

- **Statements:** Each statement terminates with a semicolon “;”.
- **Spacing:** Code indentation does not matter. Arbitrary white spaces are allowed between different components.

1.2 Comments

A comment starts with “//” and contains all text up to the end of the line.

1.3 Variables

- **Naming:** Variable names must start with a letter and may contain the following characters: lowercase letters “a”...“z”, uppercase letters “A”...“Z”, digits “1”...“9”, and underscore “_”.
- **Assignment:** Figure 1 presents the syntax for assignment statements.
- **Types:** Each variable may belong to one of three types: integer, array, or file. The type of each variable remains unchanged during its lifetime.
- **Definition:** To define a new variable, assign it a value of the desired type.
- **Scoping:** Integer and array variables are local and must be defined inside functions. File variables are global and must be defined before all functions.

Example: Figure 2 presents an example program that defines variables. The program defines a file variable `f` for an input file named “data”, an integer variable `i` of value 7, and an array `a` consisting of 12 integers.

1.4 System output

Figure 3 presents the syntax for `print` statements. A `print` statement takes the lowest byte (8 bits) of the argument, converts the byte to display form, and prints it on the screen. Table 4 describes the display form.

1.5 Assertions

Figure 4 presents the syntax for `assert` statements. An `assert` statement triggers an error when the specified condition is “false” (evaluates to zero).

```
x = some_expression;
// x becomes the result of some_expression.
```

Figure 1: Syntax for variable assignments

```
f = open("data");
main {
  i = 7;
  a = malloc(12);
  // Do something here.
  return 0;
}
```

Figure 2: Example variable assignments

```
print(some_expression);
// Output the lowest byte in the result of some_expression.
```

Figure 3: Syntax for system output

```
assert(condition);
// If condition is false, trigger an error.
// If condition is true, this is a no-op.
```

Figure 4: Syntax for assertions

Table 4: System output display form

Byte value	Display form
9	horizontal tab (' <code>\t</code> ')
10	new line (' <code>\n</code> ')
32	space (' <code> </code> ')
33 ... 126	the ASCII character for the value
others	a backslash " <code>\</code> " followed by the value

2 Data operations

2.1 Integers

- **Representation:** All integers are 32-bit two's-complement integers.
- **Boolean conversion:** When using integers in logical expressions, value 0 is “false” and non-zero values are “true”. When using logical expressions in arithmetic operations, value “false” is 0 and value “true” is 1.
- **Operators:** Tables 5, 6, and 7 describe arithmetic operators, logical operators, and brackets, respectively. Table 8 lists the precedence and associativity of these operators in descending precedence. There are no self-modifying operators such as “++” and “+=” in C.

2.2 Arrays

- **Allocation and deallocation:** Figure 5 presents the syntax for array allocation and deallocation. To allocate an array, the `malloc` statement requests space of a given size from the system memory, initializes all elements to 0, and assigns the space to an array variable. To deallocate an existing array, the `free` statement returns its space to the system for future allocation and makes the array variable invalid.
- **Reading and writing:** To read or write an element in an array, use a pair of brackets “[]” to surround the index of the element. The indices range from 0 to (n-1) for arrays with n elements. There are no multi-dimensional arrays as in C.

Example: Figure 6 presents example code for array operations. The code allocates an array `a` with two integers, updates the elements to 1 0, updates variable `x` to 0, and deallocates array `a`.

2.3 Files

- **Opening:** Figure 7a presents the syntax for opening files. An `open` statement associates an input file to a file variable and initializes the input offset to the start of the file. The `open` statement must appear outside any functions.
- **Reading:** Figure 7b presents the syntax for reading files. A `read` statement returns a byte from an input file and advances the input offset by one. The receiving variable to the left is mandatory.
- **Testing the end:** The `end` predicate tests whether all bytes in the current input unit or input file has been read.
- **Seeking:** Figure 7c presents the syntax for seeking input files to specific offsets.
- **Current offset:** The `pos` expression returns the current offset of a file.

Examples: Figure 8a presents an example program that outputs the contents in file “data”. Figure 8b presents example code that seeks to the previous byte in a file.

Table 5: Arithmetic operators

Operator	Operation	Example expression	Example result
+	add	9 + 4	13
- (binary)	subtract	9 - 4	5
- (unary)	negation	-4	-4 (0xfffffc)
*	multiply	9 * 4	36
/	divide	9 / 4	2
%	modulo (remainder)	9 % 4	1
&	bitwise AND	9 & 5	1 (0x00000001)
	bitwise OR	9 5	13 (0x0000000d)
~	bitwise NOT	~9	-10 (0xfffff6)
>>	shift right arithmetic	15 >> 2	3 (0x00000003)
<<	shift left	15 << 2	60 (0x0000003c)

Table 6: Logical operators

Operator	Operation	Example expression	Example result
==	equal to	9 == 4	0 ("false")
!=	unequal to	9 != 4	1 ("true")
<	less than	9 < 4	0 ("false")
<=	less than or equal to	9 <= 4	0 ("false")
>	greater than	9 > 4	1 ("true")
>=	greater than or equal to	9 >= 4	1 ("true")
&&	logical AND	(1 < 2) && (3 < 2)	0 ("false")
	logical OR	(1 < 2) (3 < 2)	1 ("true")
!	logical NOT	!(1 < 2)	0 ("false")

Table 8: Operator precedence and associativity

Precedence	Operator	Associativity
1	() []	left to right
2	- (unary) ~	N/A
3	* / %	left to right
4	& >> <<	left to right
5	+ - (binary)	left to right
6	== != < <= > >=	left to right
7	!	N/A
8	&&	left to right

Table 7: Brackets

Operator	Operation
()	force precedence
[]	access an array


```
arr = malloc(n);  
// If the allocation succeeds, arr becomes a valid array of n elements initialized to 0.
```

(a) Allocation

```
// arr was a valid array.  
free(arr);  
// arr becomes invalid.
```

(b) Deallocation

Figure 5: Syntax for arrays

```
a = malloc(2); // a initializes to 0 0.  
a[0] = 1; // a becomes 1 0.  
x = a[1]; // x becomes 0.  
free(a); // a becomes invalid.
```

Figure 6: Example array operations

```

f = open("data");
// If opening "data" succeeds, f becomes valid and is ready to read its 0th byte.
// Define functions here.

```

(a) Opening

```

// f was ready to read the i-th byte.
x = read(f);
// If reading succeeds, x becomes the value of the i-th byte, and f is ready to read
// the (i+1)-th byte.

```

(b) Reading

```

seek(f, x);
// f is ready to read the x-th byte.

```

(c) Seeking

Figure 7: Syntax for files

```

f = open("data");
main {
  while (!end(f)) {
    x = read(f);
    print(x);
  }
  return 0;
}

```

(a) Sequential accessing

```

| seek(f, pos(f)-1);

```

(b) Random accessing

Figure 8: Example file operations

3 Control structures

3.1 Conditional statements

Figure 9 presents the syntax for two forms of conditional statements: `if` and `if-else`. The curly braces “{}” are mandatory. There are no shorthanded “`else if`” structures as in C.

Example: Figure 10 presents example code that uses an `if` statement to set variable `i` to 5.

3.2 Loops

Figure 11 presents the syntax for `while` loops. A `while` loop repeats executing a block of code as long as a given condition holds. The curly braces “{}” are mandatory. There are no “`for`” loops as in C.

To manipulate the execution of `while` loops, `break` and `continue` statements exit the innermost surrounding loop and stop the current iteration of the innermost surrounding loop, respectively.

Examples: Figure 12 presents two pieces of example code that use `while` loops. Figure 12a is a no-op. Figure 12b contains an infinite loop.

3.3 The main function

Every program begins execution inside a special `main` function. Figure 13 presents the syntax for the `main` function.

3.4 User functions

- **Definition:** Figure 14a presents the syntax for the `func` keyword which defines user functions. Each user function may take an integer argument that is passed by value or may take no argument. Global files are accessible inside functions. Each function returns an integer value.
- **Naming:** Function names have the same rule as variable names discussed in Section 1.3.
- **Scoping:** All functions are global and must be defined in the top level of the program, parallel to the `main` function.
- **Invocation:** Figure 14b presents the syntax for calling user functions. There must be a variable that receives the return value.
- **Recursion:** User functions may be recursive, expressing operations by calling themselves.

Example: Figure 15 presents an example function, `inc`, which calculates `x` plus one.

```

if (condition) {
    // Execute if condition is true.
}

```

(a) **if**

```

if (condition) {
    // Execute if condition is true.
} else {
    // Execute if condition is false.
}

```

(b) **if-else**

Figure 9: Syntax for conditional statements

```

i = 2 - 7; // i becomes -5.
if (i < 0) { // Condition -5 < 0 is true.
    i = -i; // i becomes 5.
}

```

Figure 10: Example conditional statement

```

while (condition) {
    // Repeat executing while condition is true.
}

```

Figure 11: Syntax for **while** loops

```

while (i < 5) {
    break;
    i = i + 1;
}

```

(a) No-op

```

i = 0;
while (i < 5) {
    continue;
    i = i + 1;
}

```

(b) Infinite loop

Figure 12: Example **while** loops

```

// Open input files here.
// Define other functions here.
main {
    // Do something here.
    return some_expression;
}

```

Figure 13: Syntax for the main function

```

// Open input files here.
func foo (x) {
    // The argument is passed by value.
    // Do something here.
    return some_expression;
}
func bar () {
    // Do something here.
    return some_expression;
}
// Define other functions here.

```

y = foo(some_expression);
z = bar();

(b) Invocation

(a) Definition

Figure 14: Syntax for user functions

```

func inc (x) {
    return x + 1;
}

```

Figure 15: Example function definition

Sample Solutions

1 Summing Matrix Elements

```

// Problem 1: Summing matrix elements

f = open("input1.txt");
main {
    a = malloc(9);
    a[0] = 0; a[1] = 1; a[2] = 2;
    a[3] = 3; a[4] = 4; a[5] = 5;
    a[6] = 6; a[7] = 7; a[8] = 8;
    sum = 0;
    i0 = read(f); i0 = i0 - '0';
    //=====
    //===== YOUR CODE HERE =====
    // Hint:
    // * Read the code above.
    // * To extract the value of an ASCII digit, subtract '0'.
    // * To access row i column j of the matrix, use index i*3+j.
    // * To increment integer variable x by one, use x=x+1.
    //=====
    j0 = read(f); j0 = j0 - '0';
    r = read(f); r = r - '0';
    c = read(f); c = c - '0';
    i = i0;
    while (i < i0 + r) {
        j = j0;
        while (j < j0 + c) {
            sum = sum + a[i*3+j];
            j = j + 1;
        }
        i = i + 1;
    }
    //=====
    print(sum);
    free(a);
    return 0;
}

```

2 Converting ASCII Integers

```
// Problem 2: Converting ASCII integers

f = open("input2.txt");

//=====
//===== YOUR CODE HERE =====
// Hint:
// * Note the mandatory curly braces for conditional statements and loops.
// * A possible algorithm to parse an ASCII number is as follows:
//   ...
//   num = 0;
//   while (...) {
//       ...
//       num = num * 10 + c - '0';
//       ...
//   }
//   ...
//=====
main {
    inspect (f, '\n') {
        c = read(f);
        num = 0;
        while (c != ' ') {
            assert(c >= '0' && c <= '9');
            num = num * 10 + c - '0';
            c = read(f);
        }
        print(num);
    }
    return 0;
}
//=====
```

B.6 Control Group Instructions

Instructions

You are going to write three programs using a new programming language. Please follow the instructions below to confirm your eligibility, setup the virtual machine, learn the language, complete the writing tasks, complete surveys regarding your experience, and submit your data.

1 Eligibility

In the **past five years**, you have _____ years' experience using imperative languages _____ (such as C/C++, Java, or Python).

2 Environmental setup

1. Launch the virtual machine by opening the file “LanguageFeaturesVM.vmwarevm” with VMware Fusion.
2. Adjust the VMware window to your screen, so that you can see both the lower-left corner with a trash-can icon and the upper-right corner with a gadget icon.
3. Launch the screen recorder by clicking the blue monitor icon on the left. A window titled “vokoscreen 1.9.0” should appear. ¹
4. Click “Start” in the vokoscreen window. The vokoscreen window should minimize automatically, and there should be a small white triangle to the left of the blue monitor icon that you have previously clicked.
5. Launch a terminal by clicking the black rectangle icon on the left. A terminal window titled “default@ubuntu: ~\Desktop” should appear.

¹For analyzing purposes, we record the screen in the virtual machine as you perform tasks in this experiment. We have configured vokoscreen to record the full screen, without audio, capturing 25 frames per second, encoding in the x264 format, storing into an avi file, and including mouse cursor movements. Feel free to double check these configurations and ask the experimenter if you have any questions.

3 Language tutorial

The language used in this experiment is similar to many other imperative languages such as C.

1. Learn about the language by reading the *Language Manual*.
2. **Double-click** the file “prog0.stu” on the desktop. An editor window titled “prog0.stu (C:\Desktop) – gedit” should appear. This file contains an example program that counts the number of characters on each line of the file “input0.txt”.
3. Run this example program by entering

```
run prog0.stu
```

in the terminal. You should see

```
[Program return value]: 0.  
\5  
\3\n0
```

in the same terminal window. The first line presents the value returned from the program’s `main` function. Then follows the outputs from `print` statements. The strings “\5”, “\3”, and “\0” indicate that there are 5, 3, and 0 characters on the first, the third, and the fourth lines, respectively. The newline character between “\5” and “\3” indicates that there are 10 characters on the second line, since the number 10 corresponds to the newline character ‘\n’ in ASCII encoding.

4. Feel free to edit files “prog0.stu” and “input0.txt” and run the program again.

4 Writing tasks

There are three writing tasks. The first two tasks should help you complete the third task. Please complete them in order, and fill in the time that you start and finish each task.

4.1 Summing Matrix Elements

Started reading at _____ : _____ : _____

Your task is to fill in a program that sums up some elements in a 3×3 matrix, $\begin{pmatrix} 0 & 1 & 2 \\ 3 & 4 & 5 \\ 6 & 7 & 8 \end{pmatrix}$. An

input file specifies the elements to include. In this task and only in this task, you may assume that the input file is correct.

- **Input format:** Four ASCII-encoded digits:

- i_0 , the starting row index.
- j_0 , the starting column index.
- h , the height.
- w , the width.

These numbers satisfy that $0 \leq i_0 < i_0 + h \leq 3$ and that $0 \leq j_0 < j_0 + w \leq 3$. Row and column indices start from 0.

- **Output format:** A byte that contains the sum of the elements between rows $i_0 \dots (i_0 + h - 1)$ and columns $j_0 \dots (j_0 + w - 1)$.

Figure 1 presents sample input and output. The program sums up all elements in the last two columns of the matrix: $1 + 2 + 4 + 5 + 7 + 8 = 27$. The `print` statement displays 27 as “\27”.

0132

(a) Sample input

\27

(b) Sample output

Figure 1: Sample input and output

Finished reading at _____ : _____ : _____

Please implement this program in file “prog1.stu”, **save** the file, and run the program by entering “`run prog1.stu`” in the terminal. If there is no response, press Ctrl+C in the terminal and check if your program contains an infinite loop.

File “input1.txt” contains the sample input. Please test your program as you normally would.

Finished implementing at _____ : _____ : _____

After your implementation, please read the **sample solution** for this problem.

4.2 Converting ASCII Integers

Started reading at _____ : _____ : _____

Your task is to write a program that parses an integer preceding the first space character on each line of a file. Your program should be able to handle arbitrary inputs by skipping malformed lines.

- **Input format:** Each line starts with an ASCII-encoded, variable-length integer followed by a space character.
- **Output format:** Each output byte has the value of the leading integer from each input line.

Figure 2 presents sample input and output. Table 1 explains the sample output.

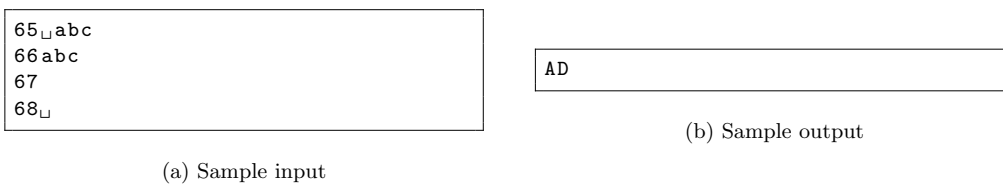


Figure 2: Sample input and output

Table 1: Explanation for sample output

Input line	Output byte	Explanation
1	65	“ <code>print(65);</code> ” displays ‘A’
2	(skipped)	unexpected character ‘a’
3	(skipped)	the trailing space character is missing
4	68	“ <code>print(68);</code> ” displays ‘D’

Finished reading at _____ : _____ : _____

Please implement this program in file “prog2.stu”, **save** the file, and run the program by entering “`run prog2.stu`” in the terminal. If there is no response, press Ctrl+C in the terminal and check if your program contains an infinite loop.

File “input2.txt” contains the sample input. Please test your program as you normally would.

Finished implementing at _____ : _____ : _____

After your implementation, please read the **sample solution** for this problem.

4.3 Image Thumbnail Generator

Started reading at _____ : _____ : _____

Your task is to write a program that generates thumbnails for multiple bitmap images in a file. Your program should be able to handle arbitrary inputs by skipping malformed images.

Image thumbnails are small images that capture the overall shape of large images. For example, a thumbnail for Figure 3 is shown in Figure 4.

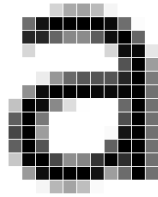


Figure 3: Magnified original image

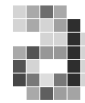


Figure 4: Magnified thumbnail

You are going to use the following algorithm that averages neighboring pixel values. Given a scaling factor s , the thumbnail for an image of height h and width w has height $\lfloor h/s \rfloor$ and width $\lfloor w/s \rfloor$. The value of the pixel in row i and column j of the thumbnail is the floor average of the values of all pixels in the s^2 square area between rows $i \cdot s \dots (i \cdot s + s - 1)$ and columns $j \cdot s \dots (j \cdot s + s - 1)$ of the original image.

- **Input format:** Each line describes an original image. Each line contains the following contents separated by a single space character:
 - An image name, which is a string of 1–10 characters long.
 - An ASCII-encoded variable-length integer, s , that represents the scaling factor.
 - An ASCII-encoded variable-length integer, h , that represents the original image height.
 - An ASCII-encoded variable-length integer, w , that represents the original image width.
 - $h \cdot w$ consecutive digits that each represents a pixel value. The pixels are ordered as follows: inside each row, pixels are ordered from left to right; the rows are each grouped together and ordered from top to bottom. Each pixel has one of ten possible values: '0'... '9'.
- **Output format:** The output contains lines that each describes a thumbnail. Each line contains the following contents separated by a single space character:
 - The image name.
 - $\lfloor h/s \rfloor \cdot \lfloor w/s \rfloor$ consecutive digits that each represents a pixel value.

Figure 5 presents sample input and output. Table 2 explains the sample output.

```

Img1_2_2_2_1234
Img2_2_4_4_1234567890123456
Img3_2_1_2_12
Img4_3_3_4_123456789012

```

(a) Sample input

```

Img1_2
Img2_3543
Img3_
Img4_3

```

(b) Sample output

Figure 5: Sample input and output

Table 2: Explanation for sample output

Name	Original	Thumbnail	Explanation
Img1	<pre> 1 2 3 4 </pre>	2	With $s = 2$, the thumbnail for Img1 has height $\lfloor 2/2 \rfloor = 1$ and width $\lfloor 2/2 \rfloor = 1$. The single pixel has the value of $\lfloor (1 + 2 + 3 + 4)/4 \rfloor = \lfloor 10/4 \rfloor = 2$.
Img2	<pre> 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 </pre>	<pre> 3 5 4 3 </pre>	With $s = 2$, the thumbnail for Img2 has height $\lfloor 4/2 \rfloor = 2$ and width $\lfloor 4/2 \rfloor = 2$. The top-left pixel in the thumbnail has the value of $\lfloor (1 + 2 + 5 + 6)/4 \rfloor = 3$. The top-right pixel in the thumbnail has the value of $\lfloor (3 + 4 + 7 + 8)/4 \rfloor = 5$. The bottom-left pixel in the thumbnail has the value of $\lfloor (9 + 0 + 3 + 4)/4 \rfloor = 4$. The bottom-right pixel in the thumbnail has the value of $\lfloor (1 + 2 + 5 + 6)/4 \rfloor = 3$.
Img3	<pre> 1 2 </pre>	(empty)	With $s = 2$, the thumbnail for Img3 has height $\lfloor 1/2 \rfloor = 0$. This height indicates that the thumbnail image is empty.
Img4	<pre> 1 2 3 4 5 6 7 8 9 0 1 2 </pre>	3	With $s = 3$, the thumbnail for Img4 has height $\lfloor 3/3 \rfloor = 1$ and width $\lfloor 4/3 \rfloor = 1$. The single pixel has the value of $\lfloor (1 + 2 + 3 + 5 + 6 + 7 + 9 + 0 + 1)/9 \rfloor = \lfloor 34/9 \rfloor = 3$.

Finished reading at _____ : _____ : _____

Please implement this program in file “prog3.stu”, **save** the file, and run the program by entering “run prog3.stu” in the terminal. If there is no response, press Ctrl+C in the terminal and check if your program contains an infinite loop.

File “input3.txt” contains the sample input. Please test your program as you normally would.

Finished implementing at _____ : _____ : _____

5 Survey

5.1 Summing Matrix Elements

Mental Demand. How mentally demanding was task 1?

Please rate from 0 (very low) to 10 (very high).

Temporal Demand. How hurried or rushed was the pace of task 1?

Please rate from 0 (very low) to 10 (very high).

Performance. How successful were you in accomplishing task 1?

Please rate from 0 (failure) to 10 (perfect).

Frustration. How insecure, discouraged, irritated, stressed, and annoyed were you?

Please rate from 0 (very low) to 10 (very high).

How many times did you cheat? Where did you cheat?

Don't worry, there is no punishment for cheating.

Any other comments or clarification?

5.2 Converting ASCII Integers

Mental Demand. How mentally demanding was task 2?

Please rate from 0 (very low) to 10 (very high).

Temporal Demand. How hurried or rushed was the pace of task 2?

Please rate from 0 (very low) to 10 (very high).

Performance. How successful were you in accomplishing task 2?

Please rate from 0 (failure) to 10 (perfect).

Frustration. How insecure, discouraged, irritated, stressed, and annoyed were you?

Please rate from 0 (very low) to 10 (very high).

How many times did you cheat? Where did you cheat?

Don't worry, there is no punishment for cheating.

Any other comments or clarification?

5.3 Image Thumbnail Generator

Mental Demand. How mentally demanding was task 3?

Please rate from 0 (very low) to 10 (very high).

Temporal Demand. How hurried or rushed was the pace of task 3?

Please rate from 0 (very low) to 10 (very high).

Performance. How successful were you in accomplishing task 3?

Please rate from 0 (failure) to 10 (perfect).

Frustration. How insecure, discouraged, irritated, stressed, and annoyed were you?

Please rate from 0 (very low) to 10 (very high).

Any other comments or clarification?

6 Submission

1. Stop the screen recorder by clicking the blue monitor icon on the left and then clicking “Stop” in the window named “vokoscreen 1.9.0”.
2. Shut down the virtual machine by clicking the gadget icon on the top-right corner, the “Shut Down...” option at the bottom of the drop-down menu, and the “Shut Down” icon on the right. DO NOT shut down from the VMware menu.
3. Send your updated file “LanguageFeaturesVM.vmwarevm” back to the experimenter.
4. Turn in this document.

B.7 Control Group Tutorials, Part I—Language

Language Manual

This manual presents a subset of a programming language that contains simplified C constructs. For quick references, Tables 1, 2, and 3 list the sections that explain basic syntax, data operations, and control structures, respectively.

Table 1: Basic syntax

Keyword	Description	Section
	formatting	1.1
	comments	1.2
	variables	1.3
print	output an integer value	1.4

Table 2: Data operations

Keyword	Description	Section
	integer expressions	2.1
	array accesses	2.2
valid (array)	test the validity of an array variable	2.2
malloc	allocate memory for an array	2.2
free	deallocate memory from an array	2.2
valid (file)	test the validity of a file variable	2.3
open	open an input file	2.3
read	read a byte from an input file	2.3
end	test the end of the input file	2.3
seek	update the input offset	2.3
pos	return current input offset	2.3

Table 3: Control structures

Keyword	Description	Section
if/if-else	conditional statements	3.1
while	loops	3.2
break	exit the current loop	3.2
continue	skip the current loop iteration	3.2
main	define the main function where a program starts	3.3
func	define a user function	3.4
return	return a value for a function	3.4

1 Basic syntax

1.1 Formatting

- **Statements:** Each statement terminates with a semicolon “;”.
- **Spacing:** Code indentation does not matter. Arbitrary white spaces are allowed between different components.

1.2 Comments

A comment starts with “//” and contains all text up to the end of the line.

1.3 Variables

- **Naming:** Variable names must start with a letter and may contain the following characters: lowercase letters “a”...“z”, uppercase letters “A”...“Z”, digits “1”...“9”, and underscore “_”.
- **Assignment:** Figure 1 presents the syntax for assignment statements.
- **Types:** Each variable may belong to one of three types: integer, array, or file. The type of each variable remains unchanged during its lifetime.
- **Definition:** To define a new variable, assign it a value of the desired type.
- **Scoping:** Integer and array variables are local and must be defined inside functions. File variables are global and must be defined before all functions.

Example: Figure 2 presents an example program that defines variables. The program defines a file variable `f` for an input file named “data”, an integer variable `i` of value 7, and an array `a` consisting of 12 integers.

1.4 System output

Figure 3 presents the syntax for `print` statements. A `print` statement takes the lowest byte (8 bits) of the argument, converts the byte to display form, and prints it on the screen. Table 4 describes the display form.

```
x = some_expression;
// x becomes the result of some_expression.
```

Figure 1: Syntax for variable assignments

```
f = open("data");
main {
  i = 7;
  a = malloc(12);
  // Do something here.
  return 0;
}
```

Figure 2: Example variable assignments

```
print(some_expression);
// Output the lowest byte in the result of some_expression.
```

Figure 3: Syntax for system output

Table 4: System output display form

Byte value	Display form
9	horizontal tab (' <code>\t</code> ')
10	new line (' <code>\n</code> ')
32	space (' <code> </code> ')
33 ... 126	the ASCII character for the value
others	a backslash " <code>\</code> " followed by the value

2 Data operations

2.1 Integers

- **Representation:** All integers are 32-bit two's-complement integers.
- **Boolean conversion:** When using integers in logical expressions, value 0 is “false” and non-zero values are “true”. When using logical expressions in arithmetic operations, value “false” is 0 and value “true” is 1.
- **Operators:** Tables 5, 6, and 7 describe arithmetic operators, logical operators, and brackets, respectively. Table 8 lists the precedence and associativity of these operators in descending precedence. There are no self-modifying operators such as “++” and “+=” in C.

2.2 Arrays

- **Validity:** The `valid` predicate tests whether an array variable is valid.
- **Allocation and deallocation:** Figure 4 presents the syntax for array allocation and deallocation. To allocate an array, the `malloc` statement requests space of a given size from the system memory, initializes all elements to 0, and assigns the space to an array variable. To deallocate an existing array, the `free` statement returns its space to the system for future allocation and makes the array variable invalid.
- **Reading and writing:** To read or write an element in an array, use a pair of brackets “[]” to surround the index of the element. The indices range from 0 to (n-1) for arrays with n elements. There are no multi-dimensional arrays as in C.

Examples: Figure 5a presents example code for array accesses. The code allocates an array `a` with two integers, updates the elements to 1 0, and updates variable `x` to 0. Figure 5b presents example code that safely deallocates an array that may be invalid.

2.3 Files

- **Validity:** The `valid` predicate tests whether a file variable is valid.
- **Opening:** Figure 6a presents the syntax for opening files. An `open` statement associates an input file to a file variable and initializes the input offset to the start of the file. The `open` statement must appear outside any functions.
- **Reading:** Figure 6b presents the syntax for reading files. A `read` statement returns a byte from an input file and advances the input offset by one. The receiving variable to the left is mandatory. The statement returns -1 if the file variable is invalid or its offset is invalid.
- **Testing the end:** The `end` predicate tests whether all bytes in the current input file has been read. The predicate returns -1 if the file variable is invalid.
- **Seeking:** Figure 6c presents the syntax for seeking input files to specific offsets. The statement returns -1 if the file variable is invalid or the offset is invalid.
- **Current offset:** The `pos` expression returns the current offset of a file. The expression returns -1 if the file variable is invalid.

Examples: Figure 7a presents an example program that outputs the contents in file “data”. Figure 7b presents example code that seeks to the previous byte in a file.

Table 5: Arithmetic operators

Operator	Operation	Example expression	Example result
+	add	9 + 4	13
- (binary)	subtract	9 - 4	5
- (unary)	negation	-4	-4 (0xfffffc)
*	multiply	9 * 4	36
/	divide	9 / 4	2
%	modulo (remainder)	9 % 4	1
&	bitwise AND	9 & 5	1 (0x00000001)
	bitwise OR	9 5	13 (0x0000000d)
~	bitwise NOT	~9	-10 (0xfffff6)
>>	shift right arithmetic	15 >> 2	3 (0x00000003)
<<	shift left	15 << 2	60 (0x0000003c)

Table 6: Logical operators

Operator	Operation	Example expression	Example result
==	equal to	9 == 4	0 ("false")
!=	unequal to	9 != 4	1 ("true")
<	less than	9 < 4	0 ("false")
<=	less than or equal to	9 <= 4	0 ("false")
>	greater than	9 > 4	1 ("true")
>=	greater than or equal to	9 >= 4	1 ("true")
&&	logical AND	(1 < 2) && (3 < 2)	0 ("false")
	logical OR	(1 < 2) (3 < 2)	1 ("true")
!	logical NOT	!(1 < 2)	0 ("false")

Table 8: Operator precedence and associativity

Precedence	Operator	Associativity
1	() []	left to right
2	- (unary) ~	N/A
3	* / %	left to right
4	& >> <<	left to right
5	+ - (binary)	left to right
6	== != < <= > >=	left to right
7	!	N/A
8	&&	left to right

Table 7: Brackets

Operator	Operation
()	force precedence
[]	access an array

```
| arr = malloc(n);  
| // If the allocation succeeds, arr becomes a valid array of n elements initialized to 0.
```

(a) Allocation

```
| // arr was a valid array.  
| free(arr);  
| // arr becomes invalid.
```

(b) Deallocation

Figure 4: Syntax for arrays

```
| a = malloc(2); // a initializes to 0 0.  
| a[0] = 1; // a becomes 1 0.  
| x = a[1]; // x becomes 0.
```

(a) Accessing

```
| // a may or may not be valid.  
| if (valid(a)) {  
|     free(a);  
| }  
| // a becomes invalid.
```

(b) Deallocating

Figure 5: Example array operations


```
f = open("data");
// If opening "data" succeeds, f becomes valid and is ready to read its 0th byte.
// Define functions here.
```

(a) Opening

```
// f was ready to read the i-th byte.
x = read(f);
// If reading succeeds, x becomes the value of the i-th byte, and f is ready to read
// the (i+1)-th byte.
// If reading fails, x becomes -1.
```

(b) Reading

```
y = seek(f, x);
// If seeking succeeds, y becomes x, and f is ready to read the x-th byte.
// If seeking fails, y becomes -1.
```

(c) Seeking

Figure 6: Syntax for files

```
f = open("data");
main {
  if (!valid(f)) {
    return -1;
  }
  while (!end(f)) {
    x = read(f);
    print(x);
  }
  return 0;
}
| y = seek(f, pos(f)-1);
(b) Random accessing
```

(a) Sequential accessing

Figure 7: Example file operations

3 Control structures

3.1 Conditional statements

Figure 8 presents the syntax for two forms of conditional statements: `if` and `if-else`. The curly braces “`{}`” are mandatory. There are no shorthanded “`else if`” structures as in C.

Example: Figure 9 presents example code that uses an `if` statement to set variable `i` to 5.

3.2 Loops

Figure 10 presents the syntax for `while` loops. A `while` loop repeats executing a block of code as long as a given condition holds. The curly braces “`{}`” are mandatory. There are no “`for`” loops as in C.

To manipulate the execution of `while` loops, `break` and `continue` statements exit the innermost surrounding loop and stop the current iteration of the innermost surrounding loop, respectively.

Examples: Figure 11 presents two pieces of example code that use `while` loops. Figure 11a is a no-op. Figure 11b contains an infinite loop.

3.3 The main function

Every program begins execution inside a special `main` function. Figure 12 presents the syntax for the `main` function.

3.4 User functions

- **Definition:** Figure 13a presents the syntax for the `func` keyword which defines user functions. Each user function may take an integer argument that is passed by value or may take no argument. Global files are accessible inside functions. Each function returns an integer value.
- **Naming:** Function names have the same rule as variable names discussed in Section 1.3.
- **Scoping:** All functions are global and must be defined in the top level of the program, parallel to the `main` function.
- **Invocation:** Figure 13b presents the syntax for calling user functions. There must be a variable that receives the return value.
- **Recursion:** User functions may be recursive, expressing operations by calling themselves.

Example: Figure 14 presents an example function, `inc`, which calculates `x` plus one.

```

if (condition) {
    // Execute if condition is true.
}

```

(a) **if**

```

if (condition) {
    // Execute if condition is true.
} else {
    // Execute if condition is false.
}

```

(b) **if-else**

Figure 8: Syntax for conditional statements

```

i = 2 - 7; // i becomes -5.
if (i < 0) { // Condition -5 < 0 is true.
    i = -i; // i becomes 5.
}

```

Figure 9: Example conditional statement

```

while (condition) {
    // Repeat executing while condition is true.
}

```

Figure 10: Syntax for **while** loops

```

while (i < 5) {
    break;
    i = i + 1;
}

```

(a) No-op

```

i = 0;
while (i < 5) {
    continue;
    i = i + 1;
}

```

(b) Infinite loop

Figure 11: Example **while** loops

```

// Open input files here.
// Define other functions here.
main {
    // Do something here.
    return some_expression;
}

```

Figure 12: Syntax for the main function

```

// Open input files here.
func foo (x) {
    // The argument is passed by value.
    // Do something here.
    return some_expression;
}
func bar () {
    // Do something here.
    return some_expression;
}
// Define other functions here.

```

y = foo(some_expression);
z = bar();

(b) Invocation

(a) Definition

Figure 13: Syntax for user functions

```

func inc (x) {
    return x + 1;
}

```

Figure 14: Example function definition

Sample Solutions

1 Summing Matrix Elements

```

// Problem 1: Summing matrix elements

f = open("input1.txt");
main {
    a = malloc(9);
    a[0] = 0; a[1] = 1; a[2] = 2;
    a[3] = 3; a[4] = 4; a[5] = 5;
    a[6] = 6; a[7] = 7; a[8] = 8;
    sum = 0;
    i0 = read(f); i0 = i0 - '0';
    //=====
    //===== YOUR CODE HERE =====
    // Hint:
    // * Read the code above.
    // * To extract the value of an ASCII digit, subtract '0'.
    // * To access row i column j of the matrix, use index i*3+j.
    // * To increment integer variable x by one, use x=x+1.
    //=====
    j0 = read(f); j0 = j0 - '0';
    r = read(f); r = r - '0';
    c = read(f); c = c - '0';
    i = i0;
    while (i < i0 + r) {
        j = j0;
        while (j < j0 + c) {
            sum = sum + a[i*3+j];
            j = j + 1;
        }
        i = i + 1;
    }
    //=====
    print(sum);
    free(a);
    return 0;
}

```

2 Converting ASCII Integers

```
// Problem 2: Converting ASCII integers

f = open("input2.txt");

//=====
//===== YOUR CODE HERE =====
// Hint:
// * Note the mandatory curly braces for conditional statements and loops.
// * A possible algorithm to parse an ASCII number is as follows:
//   ...
//   num = 0;
//   while (...) {
//       ...
//       num = num * 10 + c - '0';
//       ...
//   }
//   ...
//=====
main {
    if (!valid(f)) {
        return -1;
    }
    while(!end(f)) {
        bad = 0;
        num = 0;
        c = read(f);
        while (c != ' ' && c != '\n') {
            if (c < '0' || c > '9') {
                bad = 1;
                break;
            }
            num = num * 10 + c - '0';
            c = read(f);
        }
        if (!bad && c == ' ') {
            print(num);
        }
        while (c != '\n' && !end(f)) {
            c = read(f);
        }
    }
    return 0;
}
//=====
```

C. Benchmark Programs for Other Input Formats

This appendix describes the benchmarks in detail and presents the source code for all the programs. Table 10 presents the language constructs available for the four versions of the benchmarks. More detail about these language constructs are presented in Appendix D.

C.1 CSV

CSV files store tables. A CSV file contains a title line followed by content lines. Each line contains fields that are separated by commas.

The benchmark program reads a CSV file, expecting that each field is at most 10 characters long, and that each content line has the same number of fields as the title line. The program outputs the fields and lines that do not trigger errors. In effect, the program discards fields that are longer than 10 characters, trailing fields that would otherwise make a line contain too many fields, and content lines that do not have enough fields.

C.1.1 Full RIFL Version

```

1  main {
2    f = opent("../inputs/csv/newlines.csv");
3
4    // titles
5    columns = 0;
6    inspectt (1, f, ',', '\n') {
7      title = malloc(10);
8      i = 0;
9      while (!end(f)) {
10       x = read(f);
11       title[i] = x;
12       i = i + 1;
13     }
14     if (columns > 0) {
15       print(',');
16     }
17     print(title);
18     free(title);
19     columns = columns + 1;
20   }
21   print('\n');
22   print('\n');
23
24   // contents
25   assert(columns > 0);
26   inspectt (!end(f), f, '\n') {
27     j = 0;
28     inspectt (j < columns, f, ',') {
29       field = malloc(10);
30       i = 0;
31       while (!end(f)) {
32         x = read(f);
33         field[i] = x;
34         i = i + 1;
35       }
36       if (j > 0) {
37         print(',');
38       }
39       print(field);
40       free(field);
41       j = j + 1;
42     }
43     print('\n');
44     assert(j == columns);
45   }
46   return 0;
47 }

```

Table 10: Language restrictions for four versions

Versions	Loops	System calls
Full RIFL	inspectt, inspectb, lookatt, lookatb, while	assert, malloc, free, end, pos, opent, openb, seek, read
Explicit Check	inspectt, inspectb, lookatt, lookatb, while	assert, malloc_ec, free_ec, end_ec, pos_ec, opent_ec, openb_ec, seek_ec, read_ec
Explicit Recovery	lookatt, lookatb, while	malloc_ec, free_ec, end_ec, pos_ec, opent_ec, openb_ec, seek_ec, read_ec
Conventional	while	malloc_ec, free_ec, end_ec, pos_ec, opent_ec, openb_ec, seek_ec, read_ec

C.1.2 Explicit Check Version

```

1  main {
2    f = opent("../inputs/csv/newlines.csv");
3    assert(valid(f));
4
5    // titles
6    columns = 0;
7    inspectt (1, f, ',', '\n') {
8      title = malloc_ec(10);
9      assert(valid(title));
10     i = 0;
11     while (!end_ec(f)) {
12       assert(i < 10);
13       x = read_ec(f);
14       assert(x >= 0);
15       title[i] = x;
16       i = i + 1;
17     }
18     if (columns > 0) {
19       print(',');
20     }
21     print(title);
22     x = free_ec(title);
23     columns = columns + 1;
24   }
25   print('\n');
26   print('\n');
27
28   // contents
29   assert(columns > 0);
30   inspectt (!end_ec(f), f, '\n') {
31     j = 0;
32     inspectt (j < columns, f, ',') {
33       field = malloc_ec(10);
34       assert(valid(field));
35       i = 0;
36       while (!end_ec(f)) {
37         assert(i < 10);
38         x = read_ec(f);
39         assert(x >= 0);
40         field[i] = x;
41         i = i + 1;
42       }
43       if (j > 0) {
44         print(',');
45       }
46       print(field);
47       x = free_ec(field);
48       j = j + 1;
49     }
50     print('\n');
51     assert(j == columns);
52   }

```

```

53     return 0;
54 }

```

C.1.3 Explicit Recovery Version

```

1  main {
2  f = opent_ec("../inputs/csv/newlines.csv");
3  if (!valid(f)) {
4      exit(1);
5  }
6
7  // titles
8  columns = 0;
9  lookatt (1, f, ',', '\n') {
10     title = malloc_ec(10);
11     if (valid(title)) {
12         bad = 0;
13         i = 0;
14         while (!end_ec(f) && i < 10) {
15             x = read_ec(f);
16             if (x < 0) {
17                 bad = 1;
18             }
19             title[i] = x;
20             i = i + 1;
21         }
22         if (end_ec(f) && !bad) {
23             if (columns > 0) {
24                 print(',');
25             }
26             print(title);
27             columns = columns + 1;
28         } // skip unit
29         x = free_ec(title);
30     } // skip unit
31 }
32 print('\n');
33 print('\n');
34
35 // contents
36 if (columns <= 0) {
37     exit(1);
38 }
39 buffer = malloc_ec(11 * columns);
40 if (!valid(buffer)) {
41     exit(1);
42 }
43 lookatt (!end_ec(f), f, '\n') {
44     idx = 0;
45     while (idx < 11 * columns) {
46         buffer[idx] = 0;
47         idx = idx + 1;
48     }
49     idx = 0;
50     j = 0;
51     lookatt (j < columns, f, ',') {
52         start = idx;
53         if (j > 0) {
54             buffer[idx] = ',';
55             idx = idx + 1;
56         }
57         i = 0;
58         while (!end_ec(f) && x >= 0 && i < 10) {
59             x = read_ec(f);
60             buffer[idx] = x;
61             idx = idx + 1;
62             i = i + 1;
63         }
64         if (end_ec(f) && x >= 0) {
65             j = j + 1;
66         } else { // skip unit
67             while (idx > start) {
68                 buffer[idx] = 0;
69                 idx = idx - 1;
70             }
71         }
72     }
73 }
74 if (j == columns) {
75     print(buffer);
76     print('\n');
77 } // skip unit

```

```

77 }
78 x = free_ec(buffer);
79 return 0;
80 }

```

C.1.4 Conventional Version

```

1  main {
2  f = opent_ec("../inputs/csv/newlines.csv");
3  if (!valid(f)) {
4      exit(1);
5  }
6
7  // titles
8  columns = 0;
9  finish = 0;
10 while (!finish) {
11     title = malloc_ec(10);
12     if (valid(title)) {
13         bad = 0;
14         i = 1;
15         x = read_ec(f);
16         while (!bad && x != ',' && x != '\n' && i <
17             10) {
18             if (x < 0) {
19                 bad = 1;
20             }
21             title[i] = x;
22             i = i + 1;
23             x = read_ec(f);
24         }
25         if (!bad && (x == ',' || x == '\n')) {
26             if (columns > 0) {
27                 print(',');
28             }
29             print(title);
30             columns = columns + 1;
31         } // skip unit
32         while (x >= 0 && x != ',' && x != '\n') {
33             x = read_ec(f);
34         }
35         dummy = free_ec(title);
36     } // skip unit
37     if (x < 0 || x == '\n') {
38         finish = 1;
39     }
40 }
41 print('\n');
42 print('\n');
43
44 // contents
45 if (columns <= 0) {
46     exit(1);
47 }
48 buffer = malloc_ec(11 * columns);
49 if (!valid(buffer)) {
50     exit(1);
51 }
52 while (!end_ec(f)) {
53     idx = 0;
54     while (idx < 11 * columns) {
55         buffer[idx] = 0;
56         idx = idx + 1;
57     }
58     idx = 0;
59     j = 0;
60     x = 0;
61     while (j < columns && x >= 0 && x != '\n') {
62         start = idx;
63         if (j > 0) {
64             buffer[idx] = ',';
65             idx = idx + 1;
66         }
67         i = 0;
68         x = read_ec(f);
69         while (x >= 0 && x != '\n' && x != ',' && i
70             < 10) {
71             buffer[idx] = x;
72             idx = idx + 1;
73             i = i + 1;
74             x = read_ec(f);

```



```

73     }
74     if (x == '\n' || x == ',') {
75         j = j + 1;
76     } else { // skip unit
77         while (idx > start) {
78             buffer[idx] = 0;
79             idx = idx - 1;
80         }
81     }
82     while (x >= 0 && x != '\n' && x != ',') {
83         x = read_ec(f);
84     }
85 }
86 if (j == columns) {
87     print(buffer);
88     print('\n');
89 } // skip unit
90 while (x >= 0 && x != '\n') {
91     x = read_ec(f);
92 }
93 }
94 x = free_ec(buffer);
95 return 0;
96 }

```

C.2 OBJ

OBJ files express the shapes of objects. An OBJ file contains lines that each defines a vertex or a face. Each vertex definition contains the character 'v' followed by three space-delimited decimal numbers that represent a three-dimensional position. Each face definition contains the character 'f' followed by at least three space-delimited positive integers that each refer back to a vertex. Specifically, an integer i refers to the i -th vertex that the preceding inputs define.

The benchmark program reads an OBJ file, expecting that each decimal number is at most 10 characters long. The program also checks to ensure that each integer in a face definition is at most the number of existing vertices. The program outputs the definitions of vertices and faces that do not trigger errors. In effect, the program discards the malformed numbers, the vertices that do not contain exactly three dimensions, and the faces that do not have at least three valid vertex references.

C.2.1 Full RIFL Version

```

1 f = opent("../inputs/obj/icosahedron-2.obj");
2 num = malloc(10);
3 dim = 0;
4
5 func cleannum(dummy) {
6     i = 0;
7     while (i < 10) {
8         num[i] = 0;
9         i = i + 1;
10    }
11    return 0;
12 }
13
14 func readfloat(dummy) {
15     dummy = cleannum(0);
16
17     dot = 0;
18     i = 0;
19     x = 0;
20     sign = 1;
21     while (!end(f)) {
22         c = read(f);
23         if (c == '.') {
24             assert(dot == 0);

```

```

25     dot = 1;
26 } else {
27     if (c == '-') {
28         assert(i == 0);
29         sign = -1;
30     } else {
31         assert(c >= '0' && c <= '9');
32         x = x * 10;
33         x = x + (c - '0');
34         assert(x >= 0);
35     }
36 }
37 num[i] = c;
38 i = i + 1;
39 }
40 return x * sign;
41 }
42
43 func readidx(n) {
44     dummy = cleannum(0);
45
46     idx = 0;
47     i = 0;
48     while (!end(f)) {
49         c = read(f);
50         assert(c >= '0' && c <= '9');
51         idx = idx * 10;
52         idx = idx + (c - '0');
53         assert(idx >= 0);
54         num[i] = c;
55         i = i + 1;
56     }
57
58     assert(idx >= 1 && idx <= n);
59     return idx;
60 }
61
62 main {
63     n = 0;
64     m = 0;
65     inspect (!end(f), f, '\n') {
66         c = read(f);
67         assert(c == 'v' || c == 'f');
68         space = read(f);
69         assert(space == ' ');
70         if (c == 'v') {
71             print('v');
72             dim = 0;
73             inspectt (1, f, ' ') {
74                 assert(!end(f));
75                 x = readfloat(0);
76                 print(' ');
77                 print(num);
78                 dim = dim + 1;
79             }
80             assert(dim == 3);
81             print('\n');
82             n = n + 1;
83         } else {
84             print('f');
85             dim = 0;
86             inspectt (1, f, ' ') {
87                 assert(!end(f));
88                 idx = readidx(n);
89                 print(' ');
90                 print(num);
91                 dim = dim + 1;
92             }
93             assert(dim >= 3);
94             print('\n');
95             m = m + 1;
96         }
97     }
98
99     print(n);
100    print('\n');
101    print(m);
102    print('\n');
103
104    return 0;
105 }

```

C.2.2 Explicit Check Version

```
1 f = opent_ec("../inputs/obj/icosahedron-2.obj");
2 num = malloc_ec(10);
3 dim = 0;
4
5 func cleannum(dummy) {
6     i = 0;
7     while (i < 10) {
8         num[i] = 0;
9         i = i + 1;
10    }
11    return 0;
12 }
13
14 func readfloat(dummy) {
15     dummy = cleannum(0);
16
17     dot = 0;
18     i = 0;
19     x = 0;
20     sign = 1;
21     while (!end_ec(f)) {
22         assert(i < 10);
23         c = read_ec(f);
24         if (c == '.') {
25             assert(dot == 0);
26             dot = 1;
27         } else {
28             if (c == '-') {
29                 assert(i == 0);
30                 sign = -1;
31             } else {
32                 assert(c >= '0' && c <= '9');
33                 x = x * 10;
34                 x = x + (c - '0');
35                 assert(x >= 0);
36             }
37         }
38         num[i] = c;
39         i = i + 1;
40     }
41     return x * sign;
42 }
43
44 func readidx(n) {
45     dummy = cleannum(0);
46
47     idx = 0;
48     i = 0;
49     while (!end_ec(f)) {
50         assert(i < 10);
51         c = read_ec(f);
52         assert(c >= '0' && c <= '9');
53         idx = idx * 10;
54         idx = idx + (c - '0');
55         assert(idx >= 0);
56         num[i] = c;
57         i = i + 1;
58     }
59
60     assert(idx >= 1 && idx <= n);
61     return idx;
62 }
63
64 main {
65     assert(valid(f) && valid(num));
66     n = 0;
67     m = 0;
68     inspectt (!end(f), f, '\n') {
69         c = read_ec(f);
70         assert(c == 'v' || c == 'f');
71         space = read_ec(f);
72         assert(space == ' ');
73         if (c == 'v') {
74             print('v');
75             dim = 0;
76             inspectt (1, f, ' ') {
77                 assert(!end(f));
78                 x = readfloat(0);
79                 print(' ');
```

```
80         print(num);
81         dim = dim + 1;
82     }
83     assert(dim == 3);
84     print('\n');
85     n = n + 1;
86 } else {
87     print('f');
88     dim = 0;
89     inspectt (1, f, ' ') {
90         assert(!end(f));
91         idx = readidx(n);
92         print(' ');
93         print(num);
94         dim = dim + 1;
95     }
96     assert(dim >= 3);
97     print('\n');
98     m = m + 1;
99 }
100 }
101
102 print(n);
103 print('\n');
104 print(m);
105 print('\n');
106
107 return 0;
108 }
```

C.2.3 Explicit Recovery Version

```
1 f = opent_ec("../inputs/obj/icosahedron-2.obj");
2 num = malloc_ec(100);
3 numidx = 0;
4 dim = 0;
5
6 bad = 0;
7
8 func cleannum(dummy) {
9     i = 0;
10    while (i < 100) {
11        num[i] = 0;
12        i = i + 1;
13    }
14    numidx = 0;
15    return 0;
16 }
17
18 func putnum(c) {
19     if (numidx >= 100) {
20         bad = 1;
21     } else {
22         num[numidx] = c;
23         numidx = numidx + 1;
24     }
25     return 0;
26 }
27
28 func revertnum(start) {
29     while (numidx > start) {
30         numidx = numidx - 1;
31         num[numidx] = 0;
32     }
33     return 0;
34 }
35
36 func readfloat(dummy) {
37     dummy = putnum(' ');
38
39     dot = 0;
40     i = 0;
41     x = 0;
42     sign = 1;
43     while (!end_ec(f)) {
44         c = read_ec(f);
45         if (i >= 10 || numidx >= 100) {
46             bad = 1;
47         } else {
48             if (c == '.') {
49                 if (dot != 0) {
```

```

50     bad = 1;
51     }
52     dot = 1;
53     } else {
54     if (c == '-') {
55     if (i != 0) {
56     bad = 1;
57     }
58     sign = -1;
59     } else {
60     if (c >= '0' && c <= '9') {
61     x = x * 10;
62     x = x + (c - '0');
63     if (x < 0) {
64     bad = 1;
65     }
66     } else {
67     bad = 1;
68     }
69     }
70     }
71     dummy = putnum(c);
72     i = i + 1;
73     }
74     }
75     return x * sign;
76 }
77
78 func readidx(n) {
79     dummy = putnum(' ');
80
81     idx = 0;
82     i = 0;
83     while (!end_ec(f)) {
84     c = read_ec(f);
85     if (i >= 10 || numidx >= 100) {
86     bad = 1;
87     } else {
88     if (c >= '0' && c <= '9') {
89     idx = idx * 10;
90     idx = idx + (c - '0');
91     if (idx < 0) {
92     bad = 1;
93     }
94     } else {
95     bad = 1;
96     }
97     }
98     dummy = putnum(c);
99     i = i + 1;
100 }
101
102 if (!(idx >= 1 && idx <= n)) {
103     bad = 1;
104 }
105 return idx;
106 }
107
108 main {
109     if (!(valid(f) && valid(num))) {
110     exit(1);
111     }
112     n = 0;
113     m = 0;
114     lookatt (!end_ec(f), f, '\n') {
115     c = read_ec(f);
116     if (c == 'v' || c == 'f') {
117     space = read_ec(f);
118     if (space == ' ') {
119     if (c == 'v') {
120     dim = 0;
121     dummy = cleannum(0);
122     lookatt (1, f, ' ') {
123     bad = 0;
124     if (!end_ec(f)) {
125     start = numidx;
126     x = readfloat(0);
127     if (!bad) {
128     dim = dim + 1;
129     } else { // discard bad updates
130     dummy = revertnum(start);

```

```

131     }
132     }
133     }
134     if (dim == 3) {
135     print('v');
136     print(num);
137     print('\n');
138     n = n + 1;
139     } // skip unit
140     } else {
141     dim = 0;
142     dummy = cleannum(0);
143     lookatt (1, f, ' ') {
144     bad = 0;
145     if (!end_ec(f)) {
146     start = numidx;
147     idx = readidx(n);
148     if (!bad) {
149     dim = dim + 1;
150     } else { // discard bad updates
151     dummy = revertnum(start);
152     }
153     }
154     }
155     if (dim >= 3) {
156     print('f');
157     print(num);
158     print('\n');
159     m = m + 1;
160     } // skip unit
161     }
162     } // skip unit
163     } // skip unit
164     }
165
166     print(n);
167     print('\n');
168     print(m);
169     print('\n');
170
171     return 0;
172 }

```

C.2.4 Conventional Version

```

1 f = opent_ec("../inputs/obj/icosahedron-2.obj");
2 num = malloc_ec(100);
3 numidx = 0;
4 dim = 0;
5
6 bad = 0;
7 endl = 0;
8
9 func cleannum(dummy) {
10     i = 0;
11     while (i < 100) {
12     num[i] = 0;
13     i = i + 1;
14     }
15     numidx = 0;
16     return 0;
17 }
18
19 func putnum(c) {
20     if (numidx >= 100) {
21     bad = 1;
22     } else {
23     num[numidx] = c;
24     numidx = numidx + 1;
25     }
26     return 0;
27 }
28
29 func revertnum(start) {
30     while (numidx > start) {
31     numidx = numidx - 1;
32     num[numidx] = 0;
33     }
34     return 0;
35 }
36

```

```

37 func readfloat(dummy) {
38     dummy = putnum(' ');
39
40     dot = 0;
41     i = 0;
42     x = 0;
43     sign = 1;
44     c = read_ec(f);
45     while (c >= 0 && c != '\n' && c != ' ') {
46         if (i >= 10 || numidx >= 100) {
47             bad = 1;
48         } else {
49             if (c == '.') {
50                 if (dot != 0) {
51                     bad = 1;
52                 }
53                 dot = 1;
54             } else {
55                 if (c == '-') {
56                     if (i != 0) {
57                         bad = 1;
58                     }
59                     sign = -1;
60                 } else {
61                     if (c >= '0' && c <= '9') {
62                         x = x * 10;
63                         x = x + (c - '0');
64                         if (x < 0) {
65                             bad = 1;
66                         }
67                     } else {
68                         bad = 1;
69                     }
70                 }
71             }
72             dummy = putnum(c);
73             i = i + 1;
74         }
75         c = read_ec(f);
76     }
77
78     if (c != ' ') {
79         endl = 1;
80     }
81     if (i <= 0) {
82         bad = 1;
83     }
84     return x * sign;
85 }
86
87 func readidx(n) {
88     dummy = putnum(' ');
89
90     idx = 0;
91     i = 0;
92     c = read_ec(f);
93     while (c >= 0 && c != '\n' && c != ' ') {
94         if (i >= 10 || numidx >= 100) {
95             bad = 1;
96         } else {
97             if (c >= '0' && c <= '9') {
98                 idx = idx * 10;
99                 idx = idx + (c - '0');
100                if (idx < 0) {
101                    bad = 1;
102                }
103            } else {
104                bad = 1;
105            }
106        }
107        dummy = putnum(c);
108        i = i + 1;
109        c = read_ec(f);
110    }
111
112    if (c != ' ') {
113        endl = 1;
114    }
115    if (!(i > 0 && idx >= 1 && idx <= n)) {
116        bad = 1;
117    }
118
119    return idx;
120 }
121
122 main {
123     if (!(valid(f) && valid(num))) {
124         exit(1);
125     }
126     n = 0;
127     m = 0;
128     while (!end_ec(f)) {
129         c = read_ec(f);
130         if (c == 'v' || c == 'f') {
131             space = read_ec(f);
132             if (space == ' ') {
133                 if (c == 'v') {
134                     dim = 0;
135                     dummy = cleannum(0);
136                     endl = 0;
137                     while (!endl) {
138                         bad = 0;
139                         start = numidx;
140                         x = readfloat(0);
141                         if (!bad) {
142                             dim = dim + 1;
143                         } else { // discard bad updates
144                             dummy = revertnum(start);
145                         }
146                     }
147                     if (dim == 3) {
148                         print('v');
149                         print(num);
150                         print('\n');
151                         n = n + 1;
152                     } // skip unit
153                 } else {
154                     dim = 0;
155                     dummy = cleannum(0);
156                     endl = 0;
157                     while (!endl) {
158                         bad = 0;
159                         start = numidx;
160                         idx = readidx(n);
161                         if (!bad) {
162                             dim = dim + 1;
163                         } else { // discard bad updates
164                             dummy = revertnum(start);
165                         }
166                     }
167                     if (dim >= 3) {
168                         print('f');
169                         print(num);
170                         print('\n');
171                         m = m + 1;
172                     } // skip unit
173                 }
174                 dummy = seek_ec(f, pos_ec(f) - 1);
175                 c = read_ec(f);
176             } else { // skip unit
177                 c = space;
178             }
179         } // skip unit
180         while (c >= 0 && c != '\n') {
181             c = read_ec(f);
182         }
183     }
184     print(n);
185     print('\n');
186     print(m);
187     print('\n');
188
189     return 0;
190 }

```

C.3 JSON

JSON files describe object attributes. A JSON file contains a unit which we define as follows. A token is a string that does not contain commas, colons, brackets, or braces. A key-value pair contains a token, a colon, and a unit. An object is

at least one key-value pair surrounded by braces. An array is at least one unit surrounded by brackets. A unit can be a token, an object or an array. Commas separate the key-value pairs inside objects and the units inside arrays.

The benchmark program reads a JSON file, expecting that there are at most 10 tokens, and that each token is at most 20 characters long. The program outputs the contents of inputs that do not trigger errors. In effect, the program discards tokens that are longer than 20 characters, malformed key-value pairs in objects, malformed units in arrays, and units that would otherwise make the program store more than 10 tokens.

C.3.1 Full RIFL Version

```

1  tokenstart = malloc(10);
2  tokenlen = malloc(10);
3  tokentype = malloc(10);
4  tokencount = 0;
5
6  func DFS(f, level) {
7      first = read(f);
8      // remove leading whitespace
9      while (first == ' ' || first == '\n') {
10         first = read(f);
11     }
12     assert (first != ',' && first != ':' && first !=
13             '}' && first != '[');
14     if (first == '{') { // object
15         objlen = 0;
16         inspectt (1, f, ',', '}') {
17             c = read(f);
18             key = malloc(20);
19             while (c == ' ' || c == '\n') {
20                 c = read(f);
21             }
22             // parse key token
23             tokenstart[tokencount] = pos(f);
24             i = 0;
25             while (c != ':') {
26                 assert(c != '[' && c != '{');
27                 if (c == '\n') {
28                     key[i] = ' ';
29                 } else {
30                     key[i] = c;
31                 }
32                 i = i + 1;
33                 c = read(f);
34             }
35             // remove trailing whitespace
36             while (i > 0 && (key[i-1] == ' ' || key[i-1]
37                 == '\n')) {
38                 key[i-1] = 0;
39                 i = i - 1;
40             }
41             // maintain global arrays
42             tokenlen[tokencount] = i;
43             tokentype[tokencount] = 'k';
44             tokencount = tokencount + 1;
45             // print key token
46             j = 0;
47             print('\n');
48             while (j < level) {
49                 print(' ');
50                 print(' ');
51                 j = j + 1;
52             }
53             print(key);
54             free(key);
55             print(':');
56             print(' ');
57             // parse value
58             vallen = DFS(f, level + 1);
59             assert (vallen > 0);
60             objlen = objlen + vallen + 1;
61         }
62     } else { // single token
63         word = malloc(20);
64         // parse value token
65         tokenstart[tokencount] = pos(f);
66         word[0] = first;
67         i = 1;
68         while (!end(f)) {
69             c = read(f);
70             assert(c != ':');
71             if (c == '\n') {
72                 word[i] = ' ';
73             } else {
74                 word[i] = c;
75             }
76             i = i + 1;
77         }
78         // remove trailing whitespace
79         while (i > 0 && (word[i-1] == ' ' || word[i-1]
80             == '\n')) {
81             word[i-1] = 0;
82             i = i - 1;
83         }
84         // maintain global arrays
85         tokenlen[tokencount] = i;
86         tokentype[tokencount] = 'v';
87         tokencount = tokencount + 1;
88         // print value token
89         print(word);
90         free(word);
91         return i;
92     }
93 }
94
95 main {
96     f = opent("../inputs/json/widget.json");
97     total = DFS(f, 0);
98     print('\n');
99
100    print(tokencount);
101    print('\n');
102    print(tokenstart);
103    print('\n');
104    print(tokenlen);
105    print('\n');
106    print(tokentype);
107    print('\n');
108    return total;
109 }

```

C.3.2 Explicit Check Version

```

1  tokenstart = malloc_ec(10);
2  tokenlen = malloc_ec(10);
3  tokentype = malloc_ec(10);
4  tokencount = 0;
5
6  func DFS(f, level) {
7      first = read_ec(f);

```

```

8 // remove leading whitespace
9 while (first == ' ' || first == '\n') {
10     first = read_ec(f);
11 }
12 assert (first >= 0 && first != ',' && first !=
13         ':' && first != '}' && first != ']');
14 if (first == '{') { // object
15     objlen = 0;
16     inspectt (tokencount < 9, f, ',', ' '); {
17         c = read_ec(f);
18         key = malloc_ec(20);
19         assert(valid(key));
20         while (c == ' ' || c == '\n') {
21             c = read_ec(f);
22         }
23         // parse key token
24         tokenstart[tokencount] = pos_ec(f);
25         assert(tokenstart[tokencount] >= 0);
26         i = 0;
27         while (c != ':') {
28             assert(i < 20 && c >= 0 && c != '[' && c
29                 != '{');
30             if (c == '\n') {
31                 key[i] = ' ';
32             } else {
33                 key[i] = c;
34             }
35             i = i + 1;
36             c = read_ec(f);
37         }
38         // remove trailing whitespace
39         while (i > 0 && (key[i-1] == ' ' || key[i-1]
40             == '\n')) {
41             key[i-1] = 0;
42             i = i - 1;
43         }
44         // maintain global arrays
45         tokenlen[tokencount] = i;
46         tokentype[tokencount] = 'k';
47         tokencount = tokencount + 1;
48         // print key token
49         j = 0;
50         print('\n');
51         while (j < level) {
52             print(' ');
53             print(' ');
54             j = j + 1;
55         }
56         print(key);
57         dummy = free_ec(key);
58         print(':');
59         print(' ');
60         // parse value
61         vallen = DFS(f, level + 1);
62         assert (vallen > 0);
63         objlen = objlen + vallen + i;
64     }
65     return objlen;
66 } else {
67     if (first == '[') { // array
68         arrlen = 0;
69         print('\n');
70         // parse array elements
71         inspectt (1, f, ',', ' ') {
72             i = 0;
73             while (i < level) {
74                 print(' ');
75                 print(' ');
76                 i = i + 1;
77             }
78             print('-');
79             print(' ');
80             elemflen = DFS(f, level + 1);
81             assert (elemflen > 0);
82             print('\n');
83             arrlen = arrlen + elemflen;
84         }
85         return arrlen;
86     } else { // single token
87         word = malloc_ec(20);
88         assert(valid(word));

```

```

86 // parse value token
87 tokenstart[tokencount] = pos_ec(f);
88 word[0] = first;
89 i = 1;
90 while (!end_ec(f)) {
91     assert(i < 20);
92     c = read_ec(f);
93     assert(c >= 0 && c != ':');
94     if (c == '\n') {
95         word[i] = ' ';
96     } else {
97         word[i] = c;
98     }
99     i = i + 1;
100 }
101 // remove trailing whitespace
102 while (i > 0 && (word[i-1] == ' ' || word[i-1]
103     == '\n')) {
104     word[i-1] = 0;
105     i = i - 1;
106 }
107 // maintain global arrays
108 tokenlen[tokencount] = i;
109 tokentype[tokencount] = 'v';
110 tokencount = tokencount + 1;
111 // print value token
112 print(word);
113 dummy = free_ec(word);
114 return i;
115 }
116 }
117
118 main {
119     f = opent_ec("../inputs/json/widget.json");
120     assert(valid(f) && valid(tokenstart) && valid(
121         tokenlen) && valid(tokentype));
122     total = DFS(f, 0);
123     print('\n');
124     print(tokencount);
125     print('\n');
126     print(tokenstart);
127     print('\n');
128     print(tokenlen);
129     print('\n');
130     print(tokentype);
131     print('\n');
132     return total;
133 }

```

C.3.3 Explicit Recovery Version

```

1 tokenstart = malloc_ec(10);
2 tokenlen = malloc_ec(10);
3 tokentype = malloc_ec(10);
4 tokencount = 0;
5
6 stack = malloc_ec(150);
7 stackidx = 0;
8 stackbad = 0;
9
10 func putstack(c) {
11     if (stackidx >= 150) {
12         stackbad = 1;
13     } else {
14         stack[stackidx] = c;
15         stackidx = stackidx + 1;
16     }
17     return 0;
18 }
19
20 func revertstack(start) {
21     while (stackidx > start) {
22         if (stackidx < 150) {
23             stack[stackidx] = 0;
24         }
25         stackidx = stackidx - 1;
26     }
27     if (stackidx < 150) {
28         stackbad = 0;

```

```

29     }
30     return 0;
31 }
32
33 func reverttoken(start) {
34     while (tokencount > start) {
35         if (tokencount < 10) {
36             tokenstart[tokencount] = 0;
37             tokenlen[tokencount] = 0;
38             tokentype[tokencount] = 0;
39         }
40         tokencount = tokencount - 1;
41     }
42     return 0;
43 }
44
45 func DFS(f, level) {
46     first = read_ec(f);
47     // remove leading whitespace
48     while (first == ' ' || first == '\n') {
49         first = read_ec(f);
50     }
51     if (!(first >= 0 && first != ',' && first != ':'
52         && first != '}' && first != ']')) {
53         return -1;
54     }
55     if (first == '{') { // object
56         objlen = 0;
57         lookatt (tokencount < 9, f, ',', '}') {
58             bad = 0;
59             c = read_ec(f);
60             key = malloc_ec(20);
61             if (valid(key)) {
62                 while (c == ' ' || c == '\n') {
63                     c = read_ec(f);
64                 }
65                 // parse key token
66                 position = pos_ec(f);
67                 if (position < 0) {
68                     bad = 1;
69                 }
70                 i = 0;
71                 while (!bad && c != ':') {
72                     if (!(i < 20 && c >= 0 && c != '[' && c
73                         != '{')) {
74                         bad = 1;
75                     }
76                     if (c == '\n') {
77                         key[i] = ' ';
78                     } else {
79                         key[i] = c;
80                     }
81                     i = i + 1;
82                     c = read_ec(f);
83                 }
84                 if (!bad) {
85                     stackok = stackidx;
86                     tokenok = tokencount;
87                     // remove trailing whitespace
88                     while (i > 0 && (key[i-1] == ' ' || key[
89                         i-1] == '\n')) {
90                         key[i-1] = 0;
91                         i = i - 1;
92                     }
93                     // maintain global arrays
94                     tokenstart[tokencount] = position;
95                     tokenlen[tokencount] = i;
96                     tokentype[tokencount] = 'k';
97                     tokencount = tokencount + 1;
98                     // print key token
99                     j = 0;
100                    dummy = putstack('\n');
101                    while (j < level) {
102                        dummy = putstack(' ');
103                        dummy = putstack(' ');
104                        j = j + 1;
105                    }
106                    j = 0;
107                    while (j < i) {
108                        x = key[j];
109                        dummy = putstack(x);
110
111                        j = j + 1;
112                    }
113                    dummy = putstack(':');
114                    dummy = putstack(' ');
115                    // parse value
116                    vallen = DFS(f, level + 1);
117                    if (!stackbad && vallen > 0) {
118                        objlen = objlen + vallen + i;
119                    } else { // discard bad updates
120                        dummy = revertstack(stackok);
121                        dummy = reverttoken(tokenok);
122                    }
123                } // skip unit
124                dummy = free_ec(key);
125            } // skip unit
126        }
127        return objlen;
128    } else {
129        if (first == '[') { // array
130            arrlen = 0;
131            dummy = putstack('\n');
132            // parse array elements
133            lookatt (1, f, ',', ']') {
134                stackok = stackidx;
135                tokenok = tokencount;
136                i = 0;
137                while (i < level) {
138                    dummy = putstack(' ');
139                    dummy = putstack(' ');
140                    i = i + 1;
141                }
142                dummy = putstack('-');
143                dummy = putstack(' ');
144                elemmlen = DFS(f, level + 1);
145                dummy = putstack('\n');
146                if (!stackbad && elemmlen > 0) {
147                    arrlen = arrlen + elemmlen;
148                } else { // discard bad updates
149                    dummy = revertstack(stackok);
150                    dummy = reverttoken(tokenok);
151                }
152            }
153            return arrlen;
154        } else { // single token
155            word = malloc_ec(20);
156            bad = 0;
157            if (valid(word)) {
158                // parse value token
159                position = pos_ec(f);
160                if (position < 0) {
161                    bad = 1;
162                }
163                word[0] = first;
164                i = 1;
165                while (!bad && !end_ec(f)) {
166                    if (i >= 20) {
167                        bad = 1;
168                    } else {
169                        c = read_ec(f);
170                        if (!(c >= 0 && c != ':')) {
171                            bad = 1;
172                        } else {
173                            if (c == '\n') {
174                                word[i] = ' ';
175                            } else {
176                                word[i] = c;
177                            }
178                        }
179                        i = i + 1;
180                    }
181                }
182                if (!bad) {
183                    stackok = stackidx;
184                    // remove trailing whitespace
185                    while (i > 0 && (word[i-1] == ' ' ||
186                        word[i-1] == '\n')) {
187                        word[i-1] = 0;
188                        i = i - 1;
189                    }
190                    // maintain global arrays
191                    tokenstart[tokencount] = position;

```

```

187     tokenlen[tokencount] = i;
188     tokentype[tokencount] = 'v';
189     tokencount = tokencount + 1;
190     // print value token
191     j = 0;
192     while (j < i) {
193         x = word[j];
194         dummy = putstack(x);
195         j = j + 1;
196     }
197     if (stackbad) { // discard bad updates
198         dummy = revertstack(stackok);
199         dummy = reverttoken(tokencount - 1);
200         i = 0;
201     }
202     } else { // skip unit
203         i = 0;
204     }
205     dummy = free_ec(word);
206     return i;
207 } else { // skip unit
208     return -1;
209 }
210 }
211 }
212 }
213
214 main {
215     f = opent_ec("../inputs/json/widget.json");
216     if (!(valid(f) && valid(tokenstart) && valid(
217         tokenlen) && valid(tokentype) && valid(
218         stack))) {
219         exit(1);
220     }
221     total = DFS(f, 0);
222     if (total < 0) {
223         exit(1);
224     } else {
225         print(stack);
226         print('\n');
227         print(tokencount);
228         print('\n');
229         print(tokenstart);
230         print('\n');
231         print(tokenlen);
232         print('\n');
233         print(tokentype);
234         print('\n');
235     }
236     return total;
237 }

```

C.3.4 Conventional Version

```

1  tokenstart = malloc_ec(10);
2  tokenlen = malloc_ec(10);
3  tokentype = malloc_ec(10);
4  tokencount = 0;
5
6  stack = malloc_ec(150);
7  stackidx = 0;
8  stackbad = 0;
9
10 func putstack(c) {
11     if (stackidx >= 150) {
12         stackbad = 1;
13     } else {
14         stack[stackidx] = c;
15         stackidx = stackidx + 1;
16     }
17     return 0;
18 }
19
20 func revertstack(start) {
21     while (stackidx > start) {
22         if (stackidx < 150) {
23             stack[stackidx] = 0;
24         }
25         stackidx = stackidx - 1;
26     }

```

```

27     if (stackidx < 150) {
28         stackbad = 0;
29     }
30     return 0;
31 }
32
33 func reverttoken(start) {
34     while (tokencount > start) {
35         if (tokencount < 10) {
36             tokenstart[tokencount] = 0;
37             tokenlen[tokencount] = 0;
38             tokentype[tokencount] = 0;
39         }
40         tokencount = tokencount - 1;
41     }
42     return 0;
43 }
44
45 func DFS(f, level) {
46     first = read_ec(f);
47     // remove leading whitespace
48     while (first == ' ' || first == '\n') {
49         first = read_ec(f);
50     }
51     if (!(first >= 0 && first != ',' && first != ':'
52         && first != '}' && first != ']')) {
53         return -1;
54     }
55     if (first == '{') { // object
56         objlen = 0;
57         finish = 0;
58         while (tokencount < 9 && !finish) {
59             bad = 0;
60             c = read_ec(f);
61             key = malloc_ec(20);
62             if (valid(key)) {
63                 while (c == ' ' || c == '\n') {
64                     c = read_ec(f);
65                 }
66                 // parse key token
67                 position = pos_ec(f);
68                 if (position < 0) {
69                     bad = 1;
70                 }
71                 i = 0;
72                 while (!bad && c != ':' && c != ',' && c
73                     != '}' && c != ']') {
74                     if (!(i < 20 && c >= 0 && c != '[' && c
75                         != '{')) {
76                         bad = 1;
77                     }
78                     if (c == '\n') {
79                         key[i] = ' ';
80                     } else {
81                         key[i] = c;
82                     }
83                     i = i + 1;
84                     c = read_ec(f);
85                 }
86                 if (!bad) {
87                     stackok = stackidx;
88                     tokenok = tokencount;
89                     // remove trailing whitespace
90                     while (i > 0 && (key[i-1] == ' ' || key[
91                         i-1] == '\n')) {
92                         key[i-1] = 0;
93                         i = i - 1;
94                     }
95                     // maintain global arrays
96                     tokenstart[tokencount] = position;
97                     tokenlen[tokencount] = i;
98                     tokentype[tokencount] = 'k';
99                     tokencount = tokencount + 1;
100                    // print key token
101                    j = 0;
102                    dummy = putstack('\n');
103                    while (j < level) {
104                        dummy = putstack(' ');
105                        dummy = putstack(' ');
106                        j = j + 1;
107                    }

```



```

104     j = 0;
105     while (j < i) {
106         x = key[j];
107         dummy = putstack(x);
108         j = j + 1;
109     }
110     dummy = putstack(':');
111     dummy = putstack(' ');
112     // parse value
113     vallen = DFS(f, level + 1);
114     if (!stackbad && vallen > 0) {
115         objjlen = objjlen + vallen + i;
116     } else { // discard bad updates
117         dummy = revertstack(stackok);
118         dummy = reverttoken(tokenok);
119     }
120     } // skip unit
121     dummy = free_ec(key);
122 } // skip unit
123 while (c >= 0 && c != ',' && c != '}' && c
      != ']') { // end of
      unit
124     c = read_ec(f);
125 }
126 if (c < 0 || c == '}') { // end of sequence
127     finish = 1;
128 }
129 if (c == ']') { // outside delimiters
130     finish = 1;
131     dummy = seek_ec(f, pos_ec(f) - 1);
132 }
133 }
134 return objjlen;
135 } else {
136 if (first == '[') { // array
137     arrlen = 0;
138     dummy = putstack('\n');
139     // parse array elements
140     while (!finish) {
141         stackok = stackidx;
142         tokenok = tokencount;
143         i = 0;
144         while (i < level) {
145             dummy = putstack(' ');
146             dummy = putstack(' ');
147             i = i + 1;
148         }
149         dummy = putstack('-');
150         dummy = putstack(' ');
151         elemjlen = DFS(f, level + 1);
152         dummy = putstack('\n');
153         if (!stackbad && elemjlen > 0) {
154             arrlen = arrlen + elemjlen;
155         } else { // discard bad updates
156             dummy = revertstack(stackok);
157             dummy = reverttoken(tokenok);
158         }
159         c = read_ec(f);
160         while (c >= 0 && c != ',' && c != ']' && c
              != '}') { // end of
              unit
161             c = read_ec(f);
162         }
163         if (c < 0 || c == ']') { // end of sequence
164             finish = 1;
165         }
166         if (c == '}') { // outside delimiters
167             finish = 1;
168             dummy = seek_ec(f, pos_ec(f) - 1);
169         }
170     }
171     return arrlen;
172 } else { // single token
173     word = malloc_ec(20);
174     bad = 0;
175     if (valid(word)) {
176         // parse value token
177         position = pos_ec(f);
178         if (position < 0) {
179             bad = 1;
180         }
181         word[0] = first;
182         i = 1;
183         c = read_ec(f);
184         while (!bad && c >= 0 && c != ',' && c !=
              ']' && c != '}') {
185             if (i >= 20) {
186                 bad = 1;
187             } else {
188                 if (!(c >= 0 && c != ':')) {
189                     bad = 1;
190                 } else {
191                     if (c == '\n') {
192                         word[i] = ' ';
193                     } else {
194                         word[i] = c;
195                     }
196                 }
197                 i = i + 1;
198                 c = read_ec(f);
199             }
200         }
201         if (c == ',' || c == ']' || c == '}') {
202             dummy = seek_ec(f, pos_ec(f) - 1);
203         }
204         if (!bad) {
205             stackok = stackidx;
206             // remove trailing whitespace
207             while (i > 0 && (word[i-1] == ' ' ||
                word[i-1] == '\n')) {
208                 word[i-1] = 0;
209                 i = i - 1;
210             }
211             // maintain global arrays
212             tokenstart[tokencount] = position;
213             tokenlen[tokencount] = i;
214             tokentype[tokencount] = 'v';
215             tokencount = tokencount + 1;
216             // print value token
217             j = 0;
218             while (j < i) {
219                 x = word[j];
220                 dummy = putstack(x);
221                 j = j + 1;
222             }
223             if (stackbad) { // discard bad updates
224                 dummy = revertstack(stackok);
225                 dummy = reverttoken(tokencount - 1);
226                 i = 0;
227             }
228             } else { // skip unit
229                 i = 0;
230             }
231             dummy = free_ec(word);
232             return i;
233         } else { // skip unit
234             return -1;
235         }
236     }
237 }
238 }
239
240 main {
241     f = opent_ec("../inputs/json/widget.json");
242     if (!(valid(f) && valid(tokenstart) && valid(
        tokenlen) && valid(tokentype) && valid(
        stack))) {
243         exit(1);
244     }
245     total = DFS(f, 0);
246     if (total < 0) {
247         exit(1);
248     } else {
249         print(stack);
250         print('\n');
251
252         print(tokencount);
253         print('\n');
254         print(tokenstart);
255         print('\n');
256         print(tokenlen);
257         print('\n');

```

```

258     print(tokentype);
259     print('\n');
260 }
261 return total;
262 }

```

C.4 PNG

PNG files store images. A PNG file contains a magic string followed by chunks. Each chunk contains a 4-byte nonnegative length field, a 4-byte type field, “length” bytes of data, and a 4-byte cyclic redundancy code (CRC).

The benchmark program reads a PNG file, expecting that each chunk is small enough to fit in the heap memory. When a chunk length is too large, the program flushes the input until the end of the chunk and keeps parsing. The program outputs the data contents of all chunks with type “IDAT” that do not trigger errors. The program rejects PNG files with malformed headers. The program discards trailing inputs after seeing a chunk with a negative length.

C.4.1 Full RIFL Version

```

1  func readintbytes (f, n) {
2  x = 0;
3  i = 0;
4  while (i < n) {
5  byte = read(f);
6  x = x << 8;
7  x = x | byte;
8  i = i + 1;
9  }
10 return x;
11 }
12
13 main {
14 f = openb("../inputs/png0/oi4n0g16-2.png", 0);
15
16 magic = malloc(8);
17 i = 0;
18 while (i < 8) {
19 x = read(f);
20 magic[i] = x;
21 i = i + 1;
22 }
23 assert(magic[0] == 137 && magic[1] == 'P' &&
24        magic[2] == 'N' && magic[3] == 'G' && magic
25        [4] == 13 && magic[5] == 10 && magic[6] ==
26        26 && magic[7] == 10);
27
28 free(magic);
29
30 n = readintbytes(f, 4);
31 assert(n == 13);
32
33 ihdr = malloc(4);
34 i = 0;
35 while (i < 4) {
36 x = read(f);
37 ihdr[i] = x;
38 i = i + 1;
39 }
40 assert(ihdr[0] == 'I' && ihdr[1] == 'H' && ihdr
41        [2] == 'D' && ihdr[3] == 'R');
42 free(ihdr);
43
44 w = readintbytes(f, 4);
45 h = readintbytes(f, 4);
46 assert(w > 0 && h > 0);
47
48 depth = read(f);
49 color = read(f);
50 compression = read(f);
51 filter = read(f);
52 interlace = read(f);

```

```

48 assert((depth == 1 || depth == 2 || depth == 4
49        || depth == 8 || depth == 16) && color == 0
50        && compression == 0 && filter == 0 && (
51        interlace == 0 || interlace == 1));
52
53 crc = readintbytes(f, 4);
54 // check CRC
55
56 ndata = 0;
57 finish = 0;
58 type = malloc(4);
59 inspectb (!finish, f, 0, 4, 8) {
60 length = readintbytes(f, 4);
61
62 i = 0;
63 while (i < 4) {
64 x = read(f);
65 type[i] = x;
66 i = i + 1;
67 }
68 // check type legal
69
70 if (type[0] == 'I' && type[1] == 'E' && type
71     [2] == 'N' && type[3] == 'D') { //
72     IEND
73     a = read(f);
74     b = read(f);
75     c = read(f);
76     d = read(f);
77     assert(length == 0 && a == 174 && b == 66 &&
78           c == 96 && d == 130);
79     finish = 1;
80 } else {
81 bytes = malloc(length);
82 i = 0;
83 while (i < length) {
84 x = read(f);
85 bytes[i] = x;
86 i = i + 1;
87 }
88 crc = readintbytes(f, 4);
89 // check CRC
90 if (type[0] == 'I' && type[1] == 'D' && type
91     [2] == 'A' && type[3] == 'T') { //
92     IDAT
93     ndata = ndata + 1;
94 // decompress
95 // decode
96 print(bytes);
97 }
98 free(bytes);
99 }
100 }
101 free(type);
102 return 0;

```

C.4.2 Explicit Check Version

```

1  func readintbytes (f, n) {
2  x = 0;
3  i = 0;
4  while (i < n) {
5  byte = read_ec(f);
6  assert(byte >= 0);
7  x = x << 8;
8  x = x | byte;
9  i = i + 1;
10 }
11 return x;
12 }
13
14 main {
15 f = openb_ec("../inputs/png0/oi4n0g16-2.png", 0)
16 ;
17
18 magic = malloc_ec(8);
19 assert(valid(f) && valid(magic));
20 i = 0;
21 while (i < 8) {
22 x = read_ec(f);

```

```

22     assert(x >= 0);
23     magic[i] = x;
24     i = i + 1;
25 }
26 assert(magic[0] == 137 && magic[1] == 'P' &&
        magic[2] == 'N' && magic[3] == 'G' && magic
        [4] == 13 && magic[5] == 10 && magic[6] ==
        26 && magic[7] == 10);
27 x = free_ec(magic);
28
29 n = readintbytes(f, 4);
30 assert(n == 13);
31
32 ihdr = malloc_ec(4);
33 assert(valid(ihdr));
34 i = 0;
35 while (i < 4) {
36     x = read_ec(f);
37     assert(x >= 0);
38     ihdr[i] = x;
39     i = i + 1;
40 }
41 assert(ihdr[0] == 'I' && ihdr[1] == 'H' && ihdr
        [2] == 'D' && ihdr[3] == 'R');
42 x = free_ec(ihdr);
43
44 w = readintbytes(f, 4);
45 h = readintbytes(f, 4);
46 assert(w > 0 && h > 0);
47
48 depth = read_ec(f);
49 color = read_ec(f);
50 compression = read_ec(f);
51 filter = read_ec(f);
52 interlace = read_ec(f);
53 assert((depth == 1 || depth == 2 || depth == 4
        || depth == 8 || depth == 16) && color == 0
        && compression == 0 && filter == 0 && (
        interlace == 0 || interlace == 1));
54
55 crc = readintbytes(f, 4);
56 // check CRC
57
58 ndata = 0;
59 finish = 0;
60 type = malloc_ec(4);
61 assert(valid(type));
62 inspectb (!finish, f, 0, 4, 8) {
63     length = readintbytes(f, 4);
64
65     i = 0;
66     while (i < 4) {
67         x = read_ec(f);
68         assert(x >= 0);
69         type[i] = x;
70         i = i + 1;
71     }
72     // check type legal
73
74     if (type[0] == 'I' && type[1] == 'E' && type
        [2] == 'N' && type[3] == 'D') { //
        IEND
75         a = read_ec(f);
76         b = read_ec(f);
77         c = read_ec(f);
78         d = read_ec(f);
79         assert(length == 0 && a == 174 && b == 66 &&
        c == 96 && d == 130);
80         finish = 1;
81     } else {
82         assert(length > 0);
83         bytes = malloc_ec(length);
84         assert(valid(bytes));
85         i = 0;
86         while (i < length) {
87             x = read_ec(f);
88             assert(x >= 0);
89             bytes[i] = x;
90             i = i + 1;
91         }
92         crc = readintbytes(f, 4);

```

```

93     // check CRC
94     if (type[0] == 'I' && type[1] == 'D' && type
        [2] == 'A' && type[3] == 'T') { //
        IDAT
95         ndata = ndata + 1;
96         // decompress
97         // decode
98         print(bytes);
99     }
100    x = free_ec(bytes);
101 }
102 }
103 x = free_ec(type);
104 return 0;
105 }

```

C.4.3 Explicit Recovery Version

```

1 bad = 0;
2
3 func readintbytes (f, n) {
4     x = 0;
5     i = 0;
6     while (i < n && !bad) {
7         byte = read_ec(f);
8         if (byte >= 0) {
9             x = x << 8;
10            x = x | byte;
11            i = i + 1;
12        } else {
13            bad = 1;
14            return -1;
15        }
16    }
17    return x;
18 }
19
20 main {
21     f = openb_ec("../inputs/png0/oi4n0g16-2.png", 0)
        ;
22
23     magic = malloc_ec(8);
24     if (!valid(f) || !valid(magic)) {
25         exit(1);
26     }
27     i = 0;
28     while (i < 8) {
29         x = read_ec(f);
30         if (x < 0) {
31             exit(1);
32         }
33         magic[i] = x;
34         i = i + 1;
35     }
36     if (!(magic[0] == 137 && magic[1] == 'P' &&
        magic[2] == 'N' && magic[3] == 'G' && magic
        [4] == 13 && magic[5] == 10 && magic[6] ==
        26 && magic[7] == 10)) {
37         exit(1);
38     }
39     x = free_ec(magic);
40
41     n = readintbytes(f, 4);
42     if (bad || n != 13) {
43         exit(1);
44     }
45
46     ihdr = malloc_ec(4);
47     if (!valid(ihdr)) {
48         exit(1);
49     }
50     i = 0;
51     while (i < 4) {
52         x = read_ec(f);
53         if (x < 0) {
54             exit(1);
55         }
56         ihdr[i] = x;
57         i = i + 1;
58     }

```

```

59  if (!(ihdr[0] == 'I' && ihdr[1] == 'H' && ihdr
60      [2] == 'D' && ihdr[3] == 'R')) {
61      }
62  x = free_ec(ihdr);
63
64  w = readintbytes(f, 4);
65  h = readintbytes(f, 4);
66  if (bad || w <= 0 || h <= 0) {
67      exit(1);
68  }
69
70  depth = read_ec(f);
71  color = read_ec(f);
72  compression = read_ec(f);
73  filter = read_ec(f);
74  interlace = read_ec(f);
75  if (!(depth == 1 || depth == 2 || depth == 4 ||
        depth == 8 || depth == 16) || color != 0 ||
        compression != 0 || filter != 0 || !(
        interlace == 0 || interlace == 1)) {
76      exit(1);
77  }
78
79  crc = readintbytes(f, 4);
80  if (bad) {
81      exit(1);
82  }
83  // check CRC
84
85  ndata = 0;
86  finish = 0;
87  type = malloc_ec(4);
88  if (!valid(type)) {
89      exit(1);
90  }
91  lookatb (!finish, f, 0, 4, 8) {
92      bad = 0;
93      length = readintbytes(f, 4);
94
95      i = 0;
96      while (i < 4) {
97          x = read_ec(f);
98          if (x < 0) {
99              bad = 1;
100             }
101             type[i] = x;
102             i = i + 1;
103         }
104         // check type legal
105
106         if (type[0] == 'I' && type[1] == 'E' && type
            [2] == 'N' && type[3] == 'D') { //
            IEND
107             a = read_ec(f);
108             b = read_ec(f);
109             c = read_ec(f);
110             d = read_ec(f);
111             if (length == 0 && a == 174 && b == 66 && c
                == 96 && d == 130) { //
                good
112                 finish = 1;
113             } // skip unit
114         } else {
115             if (length > 0) { // good
116                 bytes = malloc_ec(length);
117                 if (valid(bytes)) {
118                     i = 0;
119                     while (i < length) {
120                         x = read_ec(f);
121                         if (x < 0) {
122                             bad = 1;
123                         }
124                         bytes[i] = x;
125                         i = i + 1;
126                     }
127                     crc = readintbytes(f, 4);
128                     // check CRC
129                     if (!bad && type[0] == 'I' && type[1] ==
                        'D' && type[2] == 'A' && type[3]

```

```

== 'T') { //
        IDAT
130         ndata = ndata + 1;
131         // decompress
132         // decode
133         print(bytes);
134     } // skip unit
135     x = free_ec(bytes);
136 } // skip unit
137 } // skip unit
138 }
139 }
140 x = free_ec(type);
141 return 0;
142 }

```

C.4.4 Conventional Version

```

1  bad = 0;
2
3  func readintbytes (f, n) {
4      x = 0;
5      i = 0;
6      while (i < n && !bad) {
7          byte = read_ec(f);
8          if (byte >= 0) {
9              x = x << 8;
10             x = x | byte;
11             i = i + 1;
12         } else {
13             bad = 1;
14             return -1;
15         }
16     }
17     return x;
18 }
19
20 main {
21     f = openb_ec("../inputs/png0/oi4n0g16-2.png", 0)
22     ;
23
24     magic = malloc_ec(8);
25     if (!valid(f) || !valid(magic)) {
26         exit(1);
27     }
28     i = 0;
29     while (i < 8) {
30         x = read_ec(f);
31         if (x < 0) {
32             exit(1);
33         }
34         magic[i] = x;
35         i = i + 1;
36     }
37     if (!(magic[0] == 137 && magic[1] == 'P' &&
38         magic[2] == 'N' && magic[3] == 'G' && magic
39         [4] == 13 && magic[5] == 10 && magic[6] ==
40         26 && magic[7] == 10)) {
41         exit(1);
42     }
43     x = free_ec(magic);
44
45     n = readintbytes(f, 4);
46     if (bad || n != 13) {
47         exit(1);
48     }
49
50     ihdr = malloc_ec(4);
51     if (!valid(ihdr)) {
52         exit(1);
53     }
54     i = 0;
55     while (i < 4) {
56         x = read_ec(f);
57         if (x < 0) {
58             exit(1);
59         }
60         ihdr[i] = x;
61         i = i + 1;
62     }

```

```

59  if (!(ihdr[0] == 'I' && ihdr[1] == 'H' && ihdr
60      [2] == 'D' && ihdr[3] == 'R')) {
61      }
62  x = free_ec(ihdr);
63
64  w = readintbytes(f, 4);
65  h = readintbytes(f, 4);
66  if (bad || w <= 0 || h <= 0) {
67      exit(1);
68  }
69
70  depth = read_ec(f);
71  color = read_ec(f);
72  compression = read_ec(f);
73  filter = read_ec(f);
74  interlace = read_ec(f);
75  if (!(depth == 1 || depth == 2 || depth == 4 ||
76      depth == 8 || depth == 16) || color != 0 ||
77      compression != 0 || filter != 0 || !(
78      interlace == 0 || interlace == 1)) {
79      exit(1);
80  }
81
82  crc = readintbytes(f, 4);
83  if (bad) {
84      exit(1);
85  }
86  // check CRC
87
88  ndata = 0;
89  finish = 0;
90  type = malloc_ec(4);
91  if (!valid(type)) {
92      exit(1);
93  }
94  while (!finish) {
95      bad = 0;
96      length = readintbytes(f, 4);
97      eou = pos_ec(f) + length + 8;
98      if (!bad && length >= 0) {
99          i = 0;
100         while (i < 4) {
101             x = read_ec(f);
102             if (x < 0) {
103                 bad = 1;
104             }
105             type[i] = x;
106             i = i + 1;
107         }
108         // check type legal
109
110         if (type[0] == 'I' && type[1] == 'E' && type
111             [2] == 'N' && type[3] == 'D') { //
112             IEND
113             a = read_ec(f);
114             b = read_ec(f);
115             c = read_ec(f);
116             d = read_ec(f);
117             if (length == 0 && a == 174 && b == 66 &&
118                 c == 96 && d == 130) { //
119                 good
120                 finish = 1;
121             } // skip unit
122         } else { // other types
123             if (length > 0) { // good
124                 bytes = malloc_ec(length);
125                 if (valid(bytes)) {
126                     i = 0;
127                     while (i < length) {
128                         x = read_ec(f);
129                         if (x < 0) {
130                             bad = 1;
131                         }
132                         bytes[i] = x;
133                         i = i + 1;
134                     }
135                     crc = readintbytes(f, 4);
136                     // check CRC
137                     if (!bad && type[0] == 'I' && type[1]
138                         == 'D' && type[2] == 'A' && type

```

```

139         [3] == 'T') { //
140             IDAT
141             ndata = ndata + 1;
142             // decompress
143             // decode
144             print(bytes);
145             } // skip unit
146             x = free_ec(bytes);
147             } // skip unit
148             } // skip unit
149             // go to next unit according to length
150             x = seek_ec(f, eou);
151             if (x < 0) { // give up
152                 finish = 1;
153             }
154             } else { // give up
155                 finish = 1;
156             }
157         }
158     }
159     x = free_ec(type);
160     return 0;
161 }

```

C.5 ZIP

ZIP files archive user files. A ZIP file contains a portion of archive data, a central directory, and an end of central directory (EOCD) record. The archive portion contains the archived user files. The central directory contains a list of records. Each record in the central directory describes meta-data of a user file and the starting offset of this user file in the archive portion. The EOCD record is at the end of the ZIP file and describes the starting offset of the central directory.

The benchmark program reads a ZIP file, iterating over the records in the central directory. The program expects that each file name and the contents for each archived user file are both short enough to fit in the heap memory. When a file name is too long, the program flushes the input until the end of the record and keeps parsing. When the contents of an archived user file is too large, the program stops parsing the current record and continues with the next record. The program outputs (a) the file names as listed in the central directory and (b) the file names and the contents in archived user files. The program rejects ZIP files with malformed EOCD records. The program discards trailing inputs after seeing a record with a negative file-name length.

C.5.1 Full RIFL Version

```

1  func readintbytesl (f, n) { // little endian
2      x = read(f);
3      if (n == 1) {
4          return x;
5      } else {
6          y = readintbytesl(f, n-1);
7          return (y << 8) + x;
8      }
9  }
10
11  main {
12      fdir = openb("../inputs/zip/stuff-1.zip", 1);
13      fent = openb("../inputs/zip/stuff-1.zip", 1);
14
15      eocd = size(fdir) - 4;
16      found = 0;
17      while (!found) {
18          seek(fdir, eocd);
19          dir_sig = readintbytesl(fdir, 4);
20          if (dir_sig == 101010256) { // 0x06054b50

```

```

21     found = 1;
22     } else {
23         eocd = eocd - 1;
24     }
25 }
26 assert(found);
27 diskid = readintbytesl(fdir, 2);
28 ndisk = readintbytesl(fdir, 2);
29 dirid = readintbytesl(fdir, 2);
30 ndir = readintbytesl(fdir, 2);
31
32 dir_size = readintbytesl(fdir, 4);
33 dir_start = readintbytesl(fdir, 4);
34 eocd_comm_size = readintbytesl(fdir, 2);
35 if (eocd_comm_size > 0) {
36     eocd_comm = malloc(eocd_comm_size);
37     i = 0;
38     while (i < eocd_comm_size) {
39         b = read(fdir);
40         eocd_comm[i] = b;
41         i = i + 1;
42     }
43 }
44
45 seek(fdir, dir_start);
46 inspectb (pos(fdir) < eocd, fdir, 28, 2, 40) {
47     dir_sig = readintbytesl(fdir, 4);
48     dir_ver_made = readintbytesl(fdir, 2);
49     dir_ver_extr = readintbytesl(fdir, 2);
50     dir_flag = readintbytesl(fdir, 2);
51     dir_comp = readintbytesl(fdir, 2);
52     dir_modif = readintbytesl(fdir, 4);
53     dir_crc = readintbytesl(fdir, 4);
54     dir_ent_size = readintbytesl(fdir, 4);
55     dir_ent_size_uncomp = readintbytesl(fdir, 4);
56     dir_name_size = readintbytesl(fdir, 2);
57     dir_extr_size = readintbytesl(fdir, 2);
58     dir_comm_size = readintbytesl(fdir, 2);
59     dir_diskid = readintbytesl(fdir, 2);
60     dir_attr = malloc(6);
61     i = 0;
62     while (i < 6) {
63         b = read(fdir);
64         dir_attr[i] = b;
65         i = i + 1;
66     }
67     dir_ent_start = readintbytesl(fdir, 4);
68     assert(dir_sig == 33639248 && dir_extr_size ==
69            24 && dir_comm_size == 0);
70     dir_name = malloc(dir_name_size);
71     i = 0;
72     while (i < dir_name_size) {
73         b = read(fdir);
74         dir_name[i] = b;
75         i = i + 1;
76     }
77     print(dir_name);
78     print('\n');
79     dir_extr = malloc(dir_extr_size);
80     i = 0;
81     while (i < dir_extr_size) {
82         b = read(fdir);
83         dir_extr[i] = b;
84         i = i + 1;
85     }
86     seek(fent, dir_ent_start);
87
88     ent_sig = readintbytesl(fent, 4);
89     ent_ver_extr = readintbytesl(fent, 2);
90     ent_flag = readintbytesl(fent, 2);
91     ent_comp = readintbytesl(fent, 2);
92     ent_modif = readintbytesl(fent, 4);
93     ent_crc = readintbytesl(fent, 4);
94     ent_ent_size = readintbytesl(fent, 4);
95     ent_ent_size_uncomp = readintbytesl(fent, 4);
96     ent_name_size = readintbytesl(fent, 2);
97     ent_extr_size = readintbytesl(fent, 2);
98
99     assert(ent_sig == 67324752 && ent_ver_extr ==
100            dir_ver_extr && ent_flag == dir_flag &&
101            ent_comp == dir_comp && ent_modif ==
102            dir_modif && ent_name_size ==
103            dir_name_size);
104     ent_name = malloc(ent_name_size);
105     i = 0;
106     while (i < ent_name_size) {
107         b = read(fent);
108         ent_name[i] = b;
109         i = i + 1;
110     }
111     print(ent_name);
112     print('\n');
113     if (ent_extr_size > 0) {
114         ent_extr = malloc(ent_extr_size);
115         i = 0;
116         while (i < ent_extr_size) {
117             b = read(fent);
118             ent_extr[i] = b;
119             i = i + 1;
120         }
121     }
122     assert(ent_flag & 8 == 0 && ent_crc == dir_crc
123            && ent_ent_size == dir_ent_size &&
124            ent_ent_size_uncomp ==
125            dir_ent_size_uncomp);
126
127     raw_data = malloc(ent_ent_size);
128     i = 0;
129     while (i < ent_ent_size) {
130         b = read(fent);
131         raw_data[i] = b;
132         i = i + 1;
133     }
134     // decompress
135     // check crc
136     print(raw_data);
137     print('\n');
138     free(ent_name);
139     free(raw_data);
140 }
141 seek(fdir, eocd);
142 return 0;
143 }

```

C.5.2 Explicit Check Version

```

1 func readintbytesl (f, n) { // little endian
2     x = read_ec(f);
3     assert(x >= 0);
4     if (n == 1) {
5         return x;
6     } else {
7         y = readintbytesl(f, n-1);
8         return (y << 8) + x;
9     }
10 }
11
12 main {
13     fdir = openb_ec("../inputs/zip/stuff-1.zip", 1);
14     fent = openb_ec("../inputs/zip/stuff-1.zip", 1);
15     assert(valid(fdir) && valid(fent));
16
17     eocd = size_ec(fdir) - 4;
18     found = 0;
19     while (!found) {
20         x = seek_ec(fdir, eocd);
21         assert(x >= 0);
22         dir_sig = readintbytesl(fdir, 4);
23         if (dir_sig == 101010256) { // 0x06054b50
24             found = 1;
25         } else {
26             eocd = eocd - 1;
27         }
28     }
29     assert(found);
30     diskid = readintbytesl(fdir, 2);
31     ndisk = readintbytesl(fdir, 2);
32     dirid = readintbytesl(fdir, 2);
33     ndir = readintbytesl(fdir, 2);
34
35     dir_size = readintbytesl(fdir, 4);

```

```

36 dir_start = readintbytesl(fdir, 4);
37 eocd_comm_size = readintbytesl(fdir, 2);
38 if (eocd_comm_size > 0) {
39     eocd_comm = malloc_ec(eocd_comm_size);
40     assert(valid(eocd_comm));
41     i = 0;
42     while (i < eocd_comm_size) {
43         b = read_ec(fdir);
44         assert(b >= 0);
45         eocd_comm[i] = b;
46         i = i + 1;
47     }
48 }
49
50 x = seek_ec(fdir, dir_start);
51 assert(x >= 0);
52 inspectb (pos_ec(fdir) < eocd && pos_ec(fdir) >=
53           0, fdir, 28, 2, 40) {
54     dir_sig = readintbytesl(fdir, 4);
55     dir_ver_made = readintbytesl(fdir, 2);
56     dir_ver_extr = readintbytesl(fdir, 2);
57     dir_flag = readintbytesl(fdir, 2);
58     dir_comp = readintbytesl(fdir, 2);
59     dir_modif = readintbytesl(fdir, 4);
60     dir_crc = readintbytesl(fdir, 4);
61     dir_ent_size = readintbytesl(fdir, 4);
62     dir_ent_size_uncomp = readintbytesl(fdir, 4);
63     dir_name_size = readintbytesl(fdir, 2);
64     dir_extr_size = readintbytesl(fdir, 2);
65     dir_comm_size = readintbytesl(fdir, 2);
66     dir_diskid = readintbytesl(fdir, 2);
67     dir_attr = malloc_ec(6);
68     assert(valid(dir_attr));
69     i = 0;
70     while (i < 6) {
71         b = read_ec(fdir);
72         assert(b >= 0);
73         dir_attr[i] = b;
74         i = i + 1;
75     }
76     dir_ent_start = readintbytesl(fdir, 4);
77     assert(dir_sig == 33639248 && dir_extr_size ==
78           24 && dir_comm_size == 0 &&
79           dir_name_size > 0);
80     dir_name = malloc_ec(dir_name_size);
81     assert(valid(dir_name));
82     i = 0;
83     while (i < dir_name_size) {
84         b = read_ec(fdir);
85         assert(b >= 0);
86         dir_name[i] = b;
87         i = i + 1;
88     }
89     print(dir_name);
90     print('\n');
91     dir_extr = malloc_ec(dir_extr_size);
92     assert(valid(dir_extr));
93     i = 0;
94     while (i < dir_extr_size) {
95         b = read_ec(fdir);
96         assert(b >= 0);
97         dir_extr[i] = b;
98         i = i + 1;
99     }
100
101     x = seek_ec(fent, dir_ent_start);
102     assert(x >= 0);
103
104     ent_sig = readintbytesl(fent, 4);
105     ent_ver_extr = readintbytesl(fent, 2);
106     ent_flag = readintbytesl(fent, 2);
107     ent_comp = readintbytesl(fent, 2);
108     ent_modif = readintbytesl(fent, 4);
109     ent_crc = readintbytesl(fent, 4);
110     ent_ent_size = readintbytesl(fent, 4);
111     ent_ent_size_uncomp = readintbytesl(fent, 4);
112     ent_name_size = readintbytesl(fent, 2);
113     ent_extr_size = readintbytesl(fent, 2);
114
115     ent_name = malloc_ec(ent_name_size);
116     assert(valid(ent_name));
117     i = 0;
118     while (i < ent_name_size) {
119         b = read_ec(fent);
120         assert(b >= 0);
121         ent_name[i] = b;
122         i = i + 1;
123     }
124     print(ent_name);
125     print('\n');
126     if (ent_extr_size > 0) {
127         ent_extr = malloc_ec(ent_extr_size);
128         assert(valid(ent_extr));
129         i = 0;
130         while (i < ent_extr_size) {
131             b = read_ec(fent);
132             assert(b >= 0);
133             ent_extr[i] = b;
134             i = i + 1;
135         }
136         assert(ent_flag & 8 == 0 && ent_crc == dir_crc
137               && ent_ent_size == dir_ent_size &&
138               ent_ent_size_uncomp ==
139               dir_ent_size_uncomp && ent_ent_size > 0);
140
141         raw_data = malloc_ec(ent_ent_size);
142         assert(valid(raw_data));
143         i = 0;
144         while (i < ent_ent_size) {
145             b = read_ec(fent);
146             assert(b >= 0);
147             raw_data[i] = b;
148             i = i + 1;
149         }
150         // decompress
151         // check crc
152         print(raw_data);
153         print('\n');
154         x = free_ec(ent_name);
155         x = free_ec(raw_data);
156     }
157     x = seek_ec(fdir, eocd);
158     return 0;
159 }

```

C.5.3 Explicit Recovery Version

```

1 bad = 0;
2
3 func readintbytesl (f, n) { // little endian
4     x = read_ec(f);
5     if (x >= 0) {
6         if (n == 1) {
7             return x;
8         } else {
9             y = readintbytesl(f, n-1);
10            if (bad) {
11                return -1;
12            }
13            return (y << 8) + x;
14        }
15    } else {
16        bad = 1;
17        return -1;
18    }
19 }
20
21 main {
22     fdir = openb_ec("../inputs/zip/stuff-1.zip", 1);
23     fent = openb_ec("../inputs/zip/stuff-1.zip", 1);
24     if (!valid(fdir) || !valid(fent)) {
25         exit(1);
26     }
27
28     eocd = size_ec(fdir) - 4;
29     found = 0;

```

```

30 while (!found) {
31     x = seek_ec(fdir, eocd);
32     if (x < 0) {
33         exit(1);
34     }
35     dir_sig = readintbytesl(fdir, 4);
36     if (dir_sig == 101010256) { // 0x06054b50
37         found = 1;
38     } else {
39         eocd = eocd - 1;
40     }
41 }
42 if (!found) {
43     exit(1);
44 }
45 diskid = readintbytesl(fdir, 2);
46 ndisk = readintbytesl(fdir, 2);
47 dirid = readintbytesl(fdir, 2);
48 ndir = readintbytesl(fdir, 2);
49
50 dir_size = readintbytesl(fdir, 4);
51 dir_start = readintbytesl(fdir, 4);
52 eocd_comm_size = readintbytesl(fdir, 2);
53 if (eocd_comm_size > 0) {
54     eocd_comm = malloc_ec(eocd_comm_size);
55     if (!valid(eocd_comm)) {
56         exit(1);
57     }
58     i = 0;
59     while (i < eocd_comm_size) {
60         b = read_ec(fdir);
61         if (b < 0) {
62             exit(1);
63         }
64         eocd_comm[i] = b;
65         i = i + 1;
66     }
67 }
68
69 x = seek_ec(fdir, dir_start);
70 if (x < 0) {
71     exit(1);
72 }
73 lookatb (pos_ec(fdir) < eocd && pos_ec(fdir) >=
74         0, fdir, 28, 2, 40) {
75     bad = 0;
76     dir_sig = readintbytesl(fdir, 4);
77     dir_ver_made = readintbytesl(fdir, 2);
78     dir_ver_extr = readintbytesl(fdir, 2);
79     dir_flag = readintbytesl(fdir, 2);
80     dir_comp = readintbytesl(fdir, 2);
81     dir_modif = readintbytesl(fdir, 4);
82     dir_crc = readintbytesl(fdir, 4);
83     dir_ent_size = readintbytesl(fdir, 4);
84     dir_ent_size_uncomp = readintbytesl(fdir, 4);
85     dir_name_size = readintbytesl(fdir, 2);
86     dir_extr_size = readintbytesl(fdir, 2);
87     dir_comm_size = readintbytesl(fdir, 2);
88     dir_diskid = readintbytesl(fdir, 2);
89     dir_attr = malloc_ec(6);
90     if (valid(dir_attr)) {
91         i = 0;
92         while (i < 6) {
93             b = read_ec(fdir);
94             if (b < 0) {
95                 bad = 1;
96             }
97             dir_attr[i] = b;
98             i = i + 1;
99         }
100        dir_ent_start = readintbytesl(fdir, 4);
101        if (dir_sig == 33639248 && dir_extr_size ==
102            24 && dir_comm_size == 0 &&
103            dir_name_size > 0) {
104            dir_name = malloc_ec(dir_name_size);
105            if (valid(dir_name)) {
106                i = 0;
107                while (i < dir_name_size) {
108                    b = read_ec(fdir);
109                    if (b < 0) {
110                        bad = 1;
111                    }
112                }
113                dir_name[i] = b;
114                i = i + 1;
115            }
116            dir_extr = malloc_ec(dir_extr_size);
117            if (valid(dir_extr)) {
118                i = 0;
119                while (i < dir_extr_size) {
120                    b = read_ec(fdir);
121                    if (b < 0) {
122                        bad = 1;
123                    }
124                    dir_extr[i] = b;
125                    i = i + 1;
126                }
127            }
128            x = seek_ec(fent, dir_ent_start);
129            if (x >= 0) {
130                ent_sig = readintbytesl(fent, 4);
131                ent_ver_extr = readintbytesl(fent,
132                    2);
133                ent_flag = readintbytesl(fent, 2);
134                ent_comp = readintbytesl(fent, 2);
135                ent_modif = readintbytesl(fent, 4);
136                ent_crc = readintbytesl(fent, 4);
137                ent_ent_size = readintbytesl(fent,
138                    4);
139                ent_ent_size_uncomp = readintbytesl(
140                    fent, 4);
141                ent_name_size = readintbytesl(fent,
142                    2);
143                ent_extr_size = readintbytesl(fent,
144                    2);
145                print(dir_name);
146                print('\n');
147                if (ent_sig == 67324752 &&
148                    ent_ver_extr == dir_ver_extr &&
149                    ent_flag == dir_flag &&
150                    ent_comp == dir_comp &&
151                    ent_modif == dir_modif &&
152                    ent_name_size == dir_name_size
153                    && ent_name_size > 0) {
154                    ent_name = malloc_ec(ent_name_size
155                        );
156                    if (valid(ent_name)) {
157                        i = 0;
158                        while (i < ent_name_size) {
159                            b = read_ec(fent);
160                            if (b < 0) {
161                                bad = 1;
162                            }
163                            ent_name[i] = b;
164                            i = i + 1;
165                        }
166                    }
167                    if (ent_extr_size > 0) {
168                        ent_extr = malloc_ec(
169                            ent_extr_size);
170                        if (valid(ent_extr)) {
171                            i = 0;
172                            while (i < ent_extr_size) {
173                                b = read_ec(fent);
174                                if (b < 0) {
175                                    bad = 1;
176                                }
177                                ent_extr[i] = b;
178                                i = i + 1;
179                            }
180                        } else {
181                            bad = 1;
182                        }
183                    }
184                }
185                if (ent_flag & 8 == 0 && ent_crc
186                    == dir_crc && ent_ent_size
187                    == dir_ent_size &&
188                    ent_ent_size_uncomp ==
189                    dir_ent_size_uncomp &&
190                    ent_name_size > 0) {
191                    raw_data = malloc_ec(
192                        ent_ent_size);

```



```

170         if (valid(raw_data)) {
171             i = 0;
172             while (i < ent_ent_size) {
173                 b = read_ec(fent);
174                 if (b < 0) {
175                     bad = 1;
176                 }
177                 raw_data[i] = b;
178                 i = i + 1;
179             }
180             // decompress
181             // check crc
182             if (!bad) {
183                 print(ent_name);
184                 print('\n');
185                 print(raw_data);
186                 print('\n');
187             } // skip unit
188             x = free_ec(ent_name);
189             x = free_ec(raw_data);
190         } // skip unit
191     } // skip unit
192 } // skip unit
193 } // skip unit
194 } // skip unit
195 } // skip unit
196 } // skip unit
197 } // skip unit
198 } // skip unit
199 }
200 x = seek_ec(fdir, eocd);
201 return 0;
202 }

```

C.5.4 Conventional Version

```

1  bad = 0;
2
3  func readintbytesl (f, n) { // little endian
4      x = read_ec(f);
5      if (x >= 0) {
6          if (n == 1) {
7              return x;
8          } else {
9              y = readintbytesl(f, n-1);
10             if (bad) {
11                 return -1;
12             }
13             return (y << 8) + x;
14         }
15     } else {
16         bad = 1;
17         return -1;
18     }
19 }
20
21 main {
22     fdir = openb_ec("../inputs/zip/stuff-1.zip", 1);
23     fent = openb_ec("../inputs/zip/stuff-1.zip", 1);
24     if (!valid(fdir) || !valid(fent)) {
25         exit(1);
26     }
27
28     eocd = size_ec(fdir) - 4;
29     found = 0;
30     while (!found) {
31         x = seek_ec(fdir, eocd);
32         if (x < 0) {
33             exit(1);
34         }
35         dir_sig = readintbytesl(fdir, 4);
36         if (dir_sig == 101010256) { // 0x06054b50
37             found = 1;
38         } else {
39             eocd = eocd - 1;
40         }
41     }
42     if (!found) {
43         exit(1);
44     }
45     diskid = readintbytesl(fdir, 2);

```

```

46     ndisk = readintbytesl(fdir, 2);
47     dirid = readintbytesl(fdir, 2);
48     ndir = readintbytesl(fdir, 2);
49
50     dir_size = readintbytesl(fdir, 4);
51     dir_start = readintbytesl(fdir, 4);
52     eocd_comm_size = readintbytesl(fdir, 2);
53     if (eocd_comm_size > 0) {
54         eocd_comm = malloc_ec(eocd_comm_size);
55         if (!valid(eocd_comm)) {
56             exit(1);
57         }
58         i = 0;
59         while (i < eocd_comm_size) {
60             b = read_ec(fdir);
61             if (b < 0) {
62                 exit(1);
63             }
64             eocd_comm[i] = b;
65             i = i + 1;
66         }
67     }
68
69     x = seek_ec(fdir, dir_start);
70     if (x < 0) {
71         exit(1);
72     }
73     finish = 0;
74     while (!finish && pos_ec(fdir) < eocd && pos_ec(
75         fdir) >= 0) {
76         bad = 0;
77         dir_sig = readintbytesl(fdir, 4);
78         dir_ver_made = readintbytesl(fdir, 2);
79         dir_ver_extr = readintbytesl(fdir, 2);
80         dir_flag = readintbytesl(fdir, 2);
81         dir_comp = readintbytesl(fdir, 2);
82         dir_modif = readintbytesl(fdir, 4);
83         dir_crc = readintbytesl(fdir, 4);
84         dir_ent_size = readintbytesl(fdir, 4);
85         dir_ent_size_uncomp = readintbytesl(fdir, 4);
86         dir_name_size = readintbytesl(fdir, 2);
87         eou = pos_ec(fdir) + dir_name_size + 40;
88         if (!bad && dir_name_size >= 0) {
89             dir_extr_size = readintbytesl(fdir, 2);
90             dir_comm_size = readintbytesl(fdir, 2);
91             dir_diskid = readintbytesl(fdir, 2);
92             dir_attr = malloc_ec(6);
93             if (!bad && valid(dir_attr)) {
94                 i = 0;
95                 while (i < 6) {
96                     b = read_ec(fdir);
97                     if (b < 0) {
98                         bad = 1;
99                     }
100                    dir_attr[i] = b;
101                    i = i + 1;
102                }
103                dir_ent_start = readintbytesl(fdir, 4);
104                if (!bad && dir_sig == 33639248 &&
105                    dir_extr_size == 24 && dir_comm_size
106                    == 0 && dir_name_size > 0) {
107                    dir_name = malloc_ec(dir_name_size);
108                    if (valid(dir_name)) {
109                        i = 0;
110                        while (i < dir_name_size) {
111                            b = read_ec(fdir);
112                            if (b < 0) {
113                                bad = 1;
114                            }
115                            dir_name[i] = b;
116                            i = i + 1;
117                        }
118                    }
119                    dir_extr = malloc_ec(dir_extr_size);
120                    if (!bad && valid(dir_extr)) {
121                        i = 0;
122                        while (i < dir_extr_size) {
123                            b = read_ec(fdir);
124                            if (b < 0) {
125                                bad = 1;
126                            }
127                            dir_extr[i] = b;

```

```

124     i = i + 1;
125 }
126
127 x = seek_ec(fent, dir_ent_start);
128 if (x >= 0) {
129     ent_sig = readintbytesl(fent, 4);
130     ent_ver_extr = readintbytesl(fent,
131                                 2);
132     ent_flag = readintbytesl(fent, 2);
133     ent_comp = readintbytesl(fent, 2);
134     ent_modif = readintbytesl(fent, 4)
135     ;
136     ent_crc = readintbytesl(fent, 4);
137     ent_ent_size = readintbytesl(fent,
138                                 4);
139     ent_ent_size_uncomp =
140         readintbytesl(fent, 4);
141     ent_name_size = readintbytesl(fent
142                                 , 2);
143     ent_extr_size = readintbytesl(fent
144                                 , 2);
145
146     print(dir_name);
147     print('\n');
148     if (ent_sig == 67324752 &&
149         ent_ver_extr == dir_ver_extr
150         && ent_flag == dir_flag &&
151         ent_comp == dir_comp &&
152         ent_modif == dir_modif &&
153         ent_name_size ==
154         dir_name_size &&
155         ent_name_size > 0) {
156         ent_name = malloc_ec(
157             ent_name_size);
158         if (valid(ent_name)) {
159             i = 0;
160             while (i < ent_name_size) {
161                 b = read_ec(fent);
162                 if (b < 0) {
163                     bad = 1;
164                 }
165                 ent_name[i] = b;
166                 i = i + 1;
167             }
168             if (ent_extr_size > 0) {
169                 ent_extr = malloc_ec(
170                     ent_extr_size);
171                 if (valid(ent_extr)) {
172                     i = 0;
173                     while (i < ent_extr_size)
174                     {
175                         b = read_ec(fent);
176                         if (b < 0) {
177                             bad = 1;
178                         }
179                         ent_extr[i] = b;
180                         i = i + 1;
181                     }
182                 } else {
183                     bad = 1;
184                 }
185             }
186         }
187         if (ent_flag & 8 == 0 &&
188             ent_crc == dir_crc &&
189             ent_ent_size ==
190             dir_ent_size &&
191             ent_ent_size_uncomp ==
192             dir_ent_size_uncomp &&
193             ent_ent_size > 0) {
194             raw_data = malloc_ec(
195                 ent_ent_size);
196             if (valid(raw_data)) {
197                 i = 0;
198                 while (i < ent_ent_size) {
199                     b = read_ec(fent);
200                     if (b < 0) {
201                         bad = 1;
202                     }
203                     raw_data[i] = b;
204                     i = i + 1;
205                 }
206             }
207         }
208     }
209 }

```

```

182     }
183     // decompress
184     // check crc
185     if (!bad) {
186         print(ent_name);
187         print('\n');
188         print(raw_data);
189         print('\n');
190     } // skip unit
191     x = free_ec(ent_name);
192     x = free_ec(raw_data);
193 } // skip unit
194 } // skip unit
195 } // skip unit
196 } // skip unit
197 } // skip unit
198 } // skip unit
199 } // skip unit
200 } // skip unit
201 } // skip unit
202 x = seek_ec(fdir, eou);
203 if (x < 0) { // give up
204     finish = 1;
205 }
206 } else { // give up
207     finish = 1;
208 }
209 }
210 x = seek_ec(fdir, eocd);
211 return 0;
212 }

```

C.6 RGIF

RGIF files store animated images. RGIF is based on the GIF format. An GIF file contains header information followed by blocks. Each block starts with one or two bytes that describe the block type, such as image data, metadata, or other extensions. Each image may contain several consecutive blocks. The RGIF format differs from GIF only in that it adds two bytes in front of each image to describe the total length of all the blocks for the image.

The benchmark program reads an RGIF file and converts it to the GIF format. When an image is corrupted, the program discards the image and keeps parsing. The program rejects RGIF files with malformed headers. The program discards trailing inputs after seeing an image with negative length.

C.6.1 Full RIFL Version

```

1  buffer = malloc(7500);
2  number = 0;
3
4  func readintbytesl (f, n) { // little endian
5      x = read(f);
6      if (n == 1) {
7          return x;
8      } else {
9          y = readintbytesl(f, n-1);
10         return (y << 8) + x;
11     }
12 }
13
14 func readblocks (f, echo) {
15     i = 0;
16     stop = 0;
17     lookatb (!stop, f, 0, 1, 0) {
18         len = read(f);
19         if (echo) {
20             print(len);
21         }
22         if (len == 0) {
23             stop = 1;

```

```

24     } else {
25         while (!end(f)) {
26             x = read(f);
27             if (echo) {
28                 print(x);
29             }
30             buffer[i] = x;
31             i = i + 1;
32         }
33     }
34 }
35 assert(stop);
36 return i;
37 }
38
39 func printintbytesl (n) {
40     b = number & 255;
41     print(b);
42     if (n == 1) {
43         return 0;
44     } else {
45         number = number >> 8;
46         dummy = printintbytesl(n - 1);
47         return 0;
48     }
49 }
50
51 main {
52     f = openb("../inputs/rgif/welcome2-block.rgif",
53              1);
54     // header block
55     header = malloc(6);
56     i = 0;
57     while (i < 6) {
58         x = read(f);
59         print(x);
60         header[i] = x;
61         i = i + 1;
62     }
63     assert(header[0] == 'G' && header[1] == 'I' &&
64            header[2] == 'F' && header[3] == '8' && (
65            header[4] == '9' || header[4] == '7') &&
66            header[5] == 'a');
67     free(header);
68
69     // logical screen descriptor
70     canvasw = readintbytesl(f, 2);
71     number = canvasw;
72     dummy = printintbytesl(2);
73     canvash = readintbytesl(f, 2);
74     number = canvash;
75     dummy = printintbytesl(2);
76     x = read(f);
77     print(x);
78     gflag = (x & 128) >> 7;
79     bpp = (x & 112) >> 4;
80     gsort = (x & 8) >> 3;
81     background = read(f);
82     print(background);
83     aspect = read(f);
84     print(aspect);
85     assert(gflag && x & 7 == bpp);
86
87     // global color table
88     nglobal = 2 << bpp;
89     gcolors = malloc(nglobal);
90     i = 0;
91     while (i < nglobal) {
92         x = readintbytesl(f, 3);
93         number = x;
94         dummy = printintbytesl(3);
95         gcolors[i] = x;
96         i = i + 1;
97     }
98
99     trailer = 0;
100    inspectb (!trailer, f, 0, 2, 1) {
101        length = readintbytesl(f, 2);
102        x = read(f);
103        if (x == 59) { // trailer block
104            print(x);
105            trailer = 1;
106        } else {
107            label = read(f);
108            if (x == 33 && (label == 255 || label ==
109                254)) {
110                if (label == 255) { // appliation extension
111                    idlen = read(f);
112                    id = malloc(idlen);
113                    i = 0;
114                    while (i < idlen) {
115                        x = read(f);
116                        id[i] = x;
117                        i = i + 1;
118                    }
119                    free(id);
120                    applen = readblocks(f, 0);
121                    app = malloc(applen);
122                    i = 0;
123                    while (i < applen) {
124                        app[i] = buffer[i];
125                        i = i + 1;
126                    }
127                } else { // comment extension
128                    commentlen = readblocks(f, 0);
129                    comments = malloc(commentlen);
130                    i = 0;
131                    while (i < commentlen) {
132                        comments[i] = buffer[i];
133                        i = i + 1;
134                    }
135                    free(comments);
136                }
137            } else {
138                if (x == 33 && label == 249) { // graphics
139                    control extension
140                    print(x);
141                    print(label);
142                    blocksize = read(f);
143                    print(blocksize);
144                    ctrleft = read(f);
145                    print(ctrleft);
146                    delay = readintbytesl(f, 2);
147                    number = delay;
148                    dummy = printintbytesl(2);
149                    transparent = read(f);
150                    print(transparent);
151                    terminator = read(f);
152                    print(terminator);
153                    assert(terminator == 0);
154                } else {
155                    assert(x != 33);
156                    seek(f, pos(f)-2);
157                }
158            }
159
160            // image descriptor
161            x = read(f);
162            assert(x == 44);
163            print(x);
164            left = readintbytesl(f, 2);
165            number = left;
166            dummy = printintbytesl(2);
167            top = readintbytesl(f, 2);
168            number = top;
169            dummy = printintbytesl(2);
170            width = readintbytesl(f, 2);
171            number = width;
172            dummy = printintbytesl(2);
173            height = readintbytesl(f, 2);
174            number = height;
175            dummy = printintbytesl(2);
176            assert(left == 0 && top == 0 && width ==
177                canvasw && height == canvash);
178            x = read(f);
179            print(x);
180            lflag = (x & 128) >> 7;
181            linterlace = (x & 64) >> 6;
182            lsort = (x & 32) >> 5;
183            lctsize = x & 7;
184
185            // local color table

```

```

179     if (lflag) {
180         nlocal = 2 << bpp;
181         lcolors = malloc(nlocal);
182         i = 0;
183         while (i < nlocal) {
184             x = readintbytesl(f, 3);
185             number = x;
186             dummy = printintbytesl(3);
187             lcolors[i] = x;
188             i = i + 1;
189         }
190     }
191     // data sub-blocks
192     lzw = read(f);
193     print(lzw);
194     datalen = readblocks(f, 1);
195     // decompress
196     // decode
197 }
198 }
199 }
200 }
201 free(buffer);
202 if (!trailer) {
203     x = 59;
204     print(x);
205 }
206 return 0;
207 }

```

C.6.2 Explicit Check Version

```

1  buffer = malloc_ec(7500);
2  number = 0;
3
4  func readintbytesl (f, n) { // little endian
5      x = read_ec(f);
6      assert(x >= 0);
7      if (n == 1) {
8          return x;
9      } else {
10         y = readintbytesl(f, n-1);
11         return (y << 8) + x;
12     }
13 }
14
15 func readblocks (f, echo) {
16     i = 0;
17     stop = 0;
18     lookatb (!stop, f, 0, 1, 0) {
19         len = read_ec(f);
20         assert(len >= 0);
21         if (echo) {
22             print(len);
23         }
24         if (len == 0) {
25             stop = 1;
26         } else {
27             while (!end_ec(f)) {
28                 x = read_ec(f);
29                 assert(x >= 0 && i < 7500);
30                 if (echo) {
31                     print(x);
32                 }
33                 buffer[i] = x;
34                 i = i + 1;
35             }
36         }
37     }
38     assert(stop);
39     return i;
40 }
41
42 func printintbytesl (n) {
43     b = number & 255;
44     print(b);
45     if (n == 1) {
46         return 0;
47     } else {
48         number = number >> 8;
49         dummy = printintbytesl(n - 1);

```

```

50     return 0;
51 }
52 }
53
54 main {
55     f = openb_ec("../inputs/rgif/welcome2-block.rgif", 1);
56     assert(valid(buffer) && valid(f));
57
58     // header block
59     header = malloc_ec(6);
60     assert(valid(header));
61     i = 0;
62     while (i < 6) {
63         x = read_ec(f);
64         assert(x >= 0);
65         print(x);
66         header[i] = x;
67         i = i + 1;
68     }
69     assert(header[0] == 'G' && header[1] == 'I' &&
70            header[2] == 'F' && header[3] == '8' && (
71            header[4] == '9' || header[4] == '7') &&
72            header[5] == 'a');
73     x = free_ec(header);
74
75     // logical screen descriptor
76     canvasw = readintbytesl(f, 2);
77     number = canvasw;
78     dummy = printintbytesl(2);
79     canvash = readintbytesl(f, 2);
80     number = canvash;
81     dummy = printintbytesl(2);
82     x = read_ec(f);
83     assert(x >= 0);
84     print(x);
85     gflag = (x & 128) >> 7;
86     bpp = (x & 112) >> 4;
87     gsort = (x & 8) >> 3;
88     background = read_ec(f);
89     print(background);
90     aspect = read_ec(f);
91     print(aspect);
92     assert(gflag && x & 7 == bpp && background >= 0
93            && aspect >= 0);
94
95     // global color table
96     nglobal = 2 << bpp;
97     gcolors = malloc_ec(nglobal);
98     assert(valid(gcolors));
99     i = 0;
100    while (i < nglobal) {
101        x = readintbytesl(f, 3);
102        number = x;
103        dummy = printintbytesl(3);
104        gcolors[i] = x;
105        i = i + 1;
106    }
107
108    trailer = 0;
109    inspectb (!trailer, f, 0, 2, 1) {
110        length = readintbytesl(f, 2);
111        x = read_ec(f);
112        assert(x >= 0);
113        if (x == 59) { // trailer block
114            print(x);
115            trailer = 1;
116        } else {
117            label = read_ec(f);
118            assert(label >= 0);
119            if (x == 33 && (label == 255 || label ==
120                254)) {
121                if (label == 255) { // appliation extension
122                    idlen = read_ec(f);
123                    assert(idlen >= 0);
124                    id = malloc_ec(idlen);
125                    assert(valid(id));
126                    i = 0;
127                    while (i < idlen) {
128                        x = read_ec(f);
129                        assert(x >= 0);

```

```

125         id[i] = x;
126         i = i + 1;
127     }
128     x = free_ec(id);
129     applen = readblocks(f, 0);
130     app = malloc_ec(applen);
131     assert(valid(app));
132     i = 0;
133     while (i < applen) {
134         app[i] = buffer[i];
135         i = i + 1;
136     }
137 } else { // comment extension
138     commentlen = readblocks(f, 0);
139     comments = malloc_ec(commentlen);
140     assert(valid(comments));
141     i = 0;
142     while (i < commentlen) {
143         comments[i] = buffer[i];
144         i = i + 1;
145     }
146     x = free_ec(comments);
147 }
148 } else {
149     if (x == 33 && label == 249) { // graphics
150         // control extension
151         print(x);
152         print(label);
153         blocksize = read_ec(f);
154         print(blocksize);
155         ctrlxt = read_ec(f);
156         print(ctrlxt);
157         delay = readintbytesl(f, 2);
158         number = delay;
159         dummy = printintbytesl(2);
160         transparent = read_ec(f);
161         print(transparent);
162         terminator = read_ec(f);
163         print(terminator);
164         assert(blocksize >= 0 && ctrlxt >= 0 &&
165             transparent >= 0 && terminator ==
166             0);
167     } else {
168         assert(x != 33);
169         x = seek_ec(f, pos_ec(f)-2);
170         assert(x >= 0);
171     }
172     // image descriptor
173     x = read_ec(f);
174     assert(x == 44);
175     print(x);
176     left = readintbytesl(f, 2);
177     number = left;
178     dummy = printintbytesl(2);
179     top = readintbytesl(f, 2);
180     number = top;
181     dummy = printintbytesl(2);
182     width = readintbytesl(f, 2);
183     number = width;
184     dummy = printintbytesl(2);
185     height = readintbytesl(f, 2);
186     number = height;
187     dummy = printintbytesl(2);
188     assert(left == 0 && top == 0 && width ==
189         canvasw && height == canvash);
190     x = read_ec(f);
191     assert(x >= 0);
192     print(x);
193     lflag = (x & 128) >> 7;
194     linterlace = (x & 64) >> 6;
195     lsort = (x & 32) >> 5;
196     lctsize = x & 7;
197     // local color table
198     if (lflag) {
199         nlocal = 2 << bpp;
200         lcolors = malloc_ec(nlocal);
201         assert(valid(lcolors));
202         i = 0;
203         while (i < nlocal) {

```

```

202         x = readintbytesl(f, 3);
203         number = x;
204         dummy = printintbytesl(3);
205         lcolors[i] = x;
206         i = i + 1;
207     }
208 }
209
210 // data sub-blocks
211 lzw = read_ec(f);
212 assert(lzw >= 0);
213 print(lzw);
214 datalen = readblocks(f, 1);
215 // decompress
216 // decode
217 }
218 }
219 }
220 x = free_ec(buffer);
221 if (!trailer) {
222     x = 59;
223     print(x);
224 }
225 return 0;
226 }

```

C.6.3 Explicit Recovery Version

```

1  buffer = malloc_ec(7500);
2  number = 0;
3  prt = 1;
4
5  bad = 0;
6  out = malloc_ec(7500);
7  outidx = 0;
8
9  func readintbytesl (f, n) { // little endian
10     x = read_ec(f);
11     if (x < 0) {
12         bad = 1;
13         return -1;
14     }
15     if (n == 1) {
16         return x;
17     } else {
18         y = readintbytesl(f, n-1);
19         if (bad) {
20             return -1;
21         }
22         return (y << 8) + x;
23     }
24 }
25
26 func readblocks (f, echo) {
27     i = 0;
28     stop = 0;
29     lookatb (!stop, f, 0, 1, 0) {
30         len = read_ec(f);
31         if (len >= 0) {
32             if (echo) {
33                 dummy = write(len);
34             }
35             if (len == 0) {
36                 stop = 1;
37             } else {
38                 while (!end_ec(f) && !bad) {
39                     x = read_ec(f);
40                     if (x >= 0 && i < 7500) {
41                         if (echo) {
42                             dummy = write(x);
43                         }
44                         buffer[i] = x;
45                         i = i + 1;
46                     } else {
47                         bad = 1;
48                     }
49                 }
50             }
51         } else {
52             bad = 1;
53         }

```

```

54 }
55 if (!stop) {
56     bad = 1;
57 }
58 return i;
59 }
60
61 func write (x) {
62     if (outidx < 7500) {
63         out[outidx] = x;
64         outidx = outidx + 1;
65         return 0;
66     } else {
67         bad = 1;
68         return -1;
69     }
70 }
71
72 func writeintbytesl (n) {
73     b = number & 255;
74     if (prt) {
75         print(b);
76     } else {
77         dummy = write(b);
78     }
79     if (n == 1) {
80         return 0;
81     } else {
82         number = number >> 8;
83         dummy = writeintbytesl(n - 1);
84         return 0;
85     }
86 }
87
88 main {
89     f = openb_ec("../inputs/rgif/welcome2-block.rgif", 1);
90     if (!valid(buffer) || !valid(out) || !valid(f)) {
91         exit(1);
92     }
93
94     // header block
95     header = malloc_ec(6);
96     if (!valid(header)) {
97         exit(1);
98     }
99     i = 0;
100    while (i < 6) {
101        x = read_ec(f);
102        if (x < 0) {
103            exit(1);
104        }
105        print(x);
106        header[i] = x;
107        i = i + 1;
108    }
109    if (!(header[0] == 'G' && header[1] == 'I' &&
110        header[2] == 'F' && header[3] == '8' && (
111        header[4] == '9' || header[4] == '7') &&
112        header[5] == 'a')) {
113        exit(1);
114    }
115    x = free_ec(header);
116
117    // logical screen descriptor
118    canvasw = readintbytesl(f, 2);
119    number = canvasw;
120    dummy = writeintbytesl(2);
121    canvash = readintbytesl(f, 2);
122    number = canvash;
123    dummy = writeintbytesl(2);
124    x = read_ec(f);
125    if (bad || x < 0) {
126        exit(1);
127    }
128    print(x);
129    gflag = (x & 128) >> 7;
130    bpp = (x & 112) >> 4;
131    gsort = (x & 8) >> 3;
132    background = read_ec(f);
133
134    print(background);
135    aspect = read_ec(f);
136    print(aspect);
137    if (!gflag || x & 7 != bpp || background < 0 ||
138        aspect < 0) {
139        exit(1);
140    }
141
142    // global color table
143    nglobal = 2 << bpp;
144    gcolors = malloc_ec(nglobal);
145    if (!valid(gcolors)) {
146        exit(1);
147    }
148    i = 0;
149    while (i < nglobal) {
150        x = readintbytesl(f, 3);
151        if (bad) {
152            exit(1);
153        }
154        number = x;
155        dummy = writeintbytesl(3);
156        gcolors[i] = x;
157        i = i + 1;
158    }
159
160    prt = 0;
161    trailer = 0;
162    lookatb (!trailer, f, 0, 2, 1) {
163        bad = 0;
164        outidx = 0;
165        length = readintbytesl(f, 2);
166        x = read_ec(f);
167        if (x >= 0) {
168            if (x == 59) { // trailer block
169                dummy = write(x);
170                trailer = 1;
171            } else {
172                label = read_ec(f);
173                if (label < 0) {
174                    bad = 1;
175                }
176                if (x == 33 && (label == 255 || label ==
177                    254)) {
178                    if (label == 255) { // appliation extension
179                        idlen = read_ec(f);
180                        if (idlen < 0) {
181                            bad = 1;
182                        }
183                        id = malloc_ec(idlen);
184                        if (valid(id)) {
185                            i = 0;
186                            while (i < idlen) {
187                                x = read_ec(f);
188                                if (x < 0) {
189                                    bad = 1;
190                                }
191                                id[i] = x;
192                                i = i + 1;
193                            }
194                        }
195                        x = free_ec(id);
196                        applen = readblocks(f, 0);
197                        app = malloc_ec(applen);
198                        if (valid(app)) {
199                            i = 0;
200                            while (i < applen) {
201                                app[i] = buffer[i];
202                                i = i + 1;
203                            }
204                        } else {
205                            bad = 1;
206                        }
207                    } else { // comment extension
208                        commentlen = readblocks(f, 0);
209                        comments = malloc_ec(commentlen);
210                        if (valid(comments)) {
211                            i = 0;
212                            while (i < commentlen) {

```

```

209         comments[i] = buffer[i];
210         i = i + 1;
211     }
212     x = free_ec(comments);
213 } else {
214     bad = 1;
215 }
216 }
217 } else {
218     if (x == 33 && label == 249) { //
219         graphics control extension
220         dummy = write(x);
221         dummy = write(label);
222         blocksize = read_ec(f);
223         dummy = write(blocksize);
224         ctrleft = read_ec(f);
225         dummy = write(ctrleft);
226         delay = readintbytesl(f, 2);
227         number = delay;
228         dummy = writeintbytesl(2);
229         transparent = read_ec(f);
230         dummy = write(transparent);
231         terminator = read_ec(f);
232         dummy = write(terminator);
233         if (blocksize < 0 || ctrleft < 0 ||
234             transparent < 0 || terminator !=
235             0) {
236             bad = 1;
237         }
238     } else {
239         if (x == 33) {
240             bad = 1;
241         }
242         x = seek_ec(f, pos_ec(f)-2);
243         if (x < 0) {
244             bad = 1;
245         }
246     }
247 }
248 // image descriptor
249 x = read_ec(f);
250 if (x != 44) {
251     bad = 1;
252 }
253 dummy = write(x);
254 left = readintbytesl(f, 2);
255 number = left;
256 dummy = writeintbytesl(2);
257 top = readintbytesl(f, 2);
258 number = top;
259 dummy = writeintbytesl(2);
260 width = readintbytesl(f, 2);
261 number = width;
262 dummy = writeintbytesl(2);
263 height = readintbytesl(f, 2);
264 number = height;
265 dummy = writeintbytesl(2);
266 if (left != 0 || top != 0 || width !=
267     canvash || height != canvash) {
268     bad = 1;
269 }
270 x = read_ec(f);
271 if (x < 0) {
272     bad = 1;
273 }
274 dummy = write(x);
275 lflag = (x & 128) >> 7;
276 linterlace = (x & 64) >> 6;
277 lsort = (x & 32) >> 5;
278 lctsize = x & 7;
279 // local color table
280 if (lflag) {
281     nlocal = 2 << bpp;
282     lcolors = malloc_ec(nlocal);
283     if (valid(lcolors)) {
284         i = 0;
285         while (i < nlocal) {
286             x = readintbytesl(f, 3);
287             number = x;
288             dummy = writeintbytesl(3);

```

```

286         lcolors[i] = x;
287         i = i + 1;
288     }
289     } else {
290         bad = 1;
291     }
292 }
293 }
294 // data sub-blocks
295 lzw = read_ec(f);
296 if (lzw < 0) {
297     bad = 1;
298 }
299 dummy = write(lzw);
300 datalen = readblocks(f, 1);
301 // decompress
302 // decode
303 }
304 }
305 } else {
306     bad = 1;
307 }
308 if (!bad) {
309     i = 0;
310     while (i < outidx) {
311         x = out[i];
312         print(x);
313         i = i + 1;
314     }
315 } // skip unit
316 }
317 x = free_ec(buffer);
318 if (!trailer) {
319     x = 59;
320     print(x);
321 }
322 return 0;
323 }

```

C.6.4 Conventional Version

```

1  buffer = malloc_ec(7500);
2  number = 0;
3  prt = 1;
4
5  bad = 0;
6  out = malloc_ec(7500);
7  outidx = 0;
8
9  func readintbytesl (f, n) { // little endian
10     x = read_ec(f);
11     if (x < 0) {
12         bad = 1;
13         return -1;
14     }
15     if (n == 1) {
16         return x;
17     } else {
18         y = readintbytesl(f, n-1);
19         if (bad) {
20             return -1;
21         }
22         return (y << 8) + x;
23     }
24 }
25
26 func readblocks (f, echo) {
27     i = 0;
28     stop = 0;
29     while (!stop) {
30         len = read_ec(f);
31         if (len >= 0) {
32             if (echo) {
33                 dummy = write(len);
34             }
35             if (len == 0) {
36                 stop = 1;
37             } else {
38                 j = 0;
39                 while (j < len) {
40                     x = read_ec(f);

```

```

41         if (x >= 0 && i < 7500) {
42             if (echo) {
43                 dummy = write(x);
44             }
45             buffer[i] = x;
46             i = i + 1;
47         } else {
48             bad = 1;
49         }
50         j = j + 1;
51     }
52 }
53 } else {
54     bad = 1;
55 }
56 }
57 return i;
58 }
59
60 func write (x) {
61     if (outidx < 7500) {
62         out[outidx] = x;
63         outidx = outidx + 1;
64         return 0;
65     } else {
66         bad = 1;
67         return -1;
68     }
69 }
70
71 func writeintbytesl (n) {
72     b = number & 255;
73     if (prt) {
74         print(b);
75     } else {
76         dummy = write(b);
77     }
78     if (n == 1) {
79         return 0;
80     } else {
81         number = number >> 8;
82         dummy = writeintbytesl(n - 1);
83         return 0;
84     }
85 }
86
87 main {
88     f = openb_ec("../inputs/rgif/welcome2-block.rgif", 1);
89     if (!valid(buffer) || !valid(out) || !valid(f))
90         exit(1);
91 }
92
93 // header block
94 header = malloc_ec(6);
95 if (!valid(header)) {
96     exit(1);
97 }
98 i = 0;
99 while (i < 6) {
100     x = read_ec(f);
101     if (x < 0) {
102         exit(1);
103     }
104     print(x);
105     header[i] = x;
106     i = i + 1;
107 }
108 if (!(header[0] == 'G' && header[1] == 'I' &&
109     header[2] == 'F' && header[3] == '8' &&
110     header[4] == '9' || header[4] == '7') &&
111     header[5] == 'a')) {
112     exit(1);
113 }
114 x = free_ec(header);
115
116 // logical screen descriptor
117 canvasw = readintbytesl(f, 2);
118 number = canvasw;
119 dummy = writeintbytesl(2);
120
121 canvash = readintbytesl(f, 2);
122 number = canvash;
123 dummy = writeintbytesl(2);
124 x = read_ec(f);
125 if (bad || x < 0) {
126     exit(1);
127 }
128 print(x);
129 gflag = (x & 128) >> 7;
130 bpp = (x & 112) >> 4;
131 gsort = (x & 8) >> 3;
132 background = read_ec(f);
133 print(background);
134 aspect = read_ec(f);
135 print(aspect);
136 if (!gflag || x & 7 != bpp || background < 0 ||
137     aspect < 0) {
138     exit(1);
139 }
140
141 // global color table
142 nglobal = 2 << bpp;
143 gcolors = malloc_ec(nglobal);
144 if (!valid(gcolors)) {
145     exit(1);
146 }
147 i = 0;
148 while (i < nglobal) {
149     x = readintbytesl(f, 3);
150     if (bad) {
151         exit(1);
152     }
153     number = x;
154     dummy = writeintbytesl(3);
155     gcolors[i] = x;
156     i = i + 1;
157 }
158
159 prt = 0;
160 trailer = 0;
161 finish = 0;
162 while (!trailer && !finish) {
163     bad = 0;
164     outidx = 0;
165     length = readintbytesl(f, 2);
166     if (length >= 0) {
167         eou = pos_ec(f) + length + 1;
168         x = read_ec(f);
169         if (x >= 0) {
170             if (x == 59) { // trailer block
171                 dummy = write(x);
172                 trailer = 1;
173             } else {
174                 label = read_ec(f);
175                 if (label < 0) {
176                     bad = 1;
177                 }
178             }
179             if (x == 33 && (label == 255 || label ==
180                 254)) {
181                 if (label == 255) { // appliation
182                     extension
183                     idlen = read_ec(f);
184                     if (idlen < 0) {
185                         bad = 1;
186                     }
187                     id = malloc_ec(idlen);
188                     if (valid(id)) {
189                         i = 0;
190                         while (i < idlen) {
191                             x = read_ec(f);
192                             if (x < 0) {
193                                 bad = 1;
194                             }
195                             id[i] = x;
196                             i = i + 1;
197                         }
198                     }
199                     x = free_ec(id);
200                     applen = readblocks(f, 0);
201                     app = malloc_ec(applen);
202                     if (valid(app)) {
203                         i = 0;

```



```

195         while (i < applen) {
196             app[i] = buffer[i];
197             i = i + 1;
198         }
199     } else {
200         bad = 1;
201     }
202 } else {
203     bad = 1;
204 }
205 } else { // comment extension
206     commentlen = readblocks(f, 0);
207     comments = malloc_ec(commentlen);
208     if (valid(comments)) {
209         i = 0;
210         while (i < commentlen) {
211             comments[i] = buffer[i];
212             i = i + 1;
213         }
214         x = free_ec(comments);
215     } else {
216         bad = 1;
217     }
218 }
219 } else {
220     if (x == 33 && label == 249) { //
221         graphics control extension
222         dummy = write(x);
223         dummy = write(label);
224         blocksize = read_ec(f);
225         dummy = write(blocksize);
226         ctrleft = read_ec(f);
227         dummy = write(ctrleft);
228         delay = readintbytesl(f, 2);
229         number = delay;
230         dummy = writeintbytesl(2);
231         transparent = read_ec(f);
232         dummy = write(transparent);
233         terminator = read_ec(f);
234         dummy = write(terminator);
235         if (blocksize < 0 || ctrleft < 0 ||
236             transparent < 0 || terminator
237             != 0) {
238             bad = 1;
239         }
240     } else {
241         if (x == 33) {
242             bad = 1;
243         }
244         x = seek_ec(f, pos_ec(f)-2);
245         if (x < 0) {
246             bad = 1;
247         }
248     }
249     // image descriptor
250     x = read_ec(f);
251     if (x != 44) {
252         bad = 1;
253     }
254     dummy = write(x);
255     left = readintbytesl(f, 2);
256     number = left;
257     dummy = writeintbytesl(2);
258     top = readintbytesl(f, 2);
259     number = top;
260     dummy = writeintbytesl(2);
261     width = readintbytesl(f, 2);
262     number = width;
263     dummy = writeintbytesl(2);
264     height = readintbytesl(f, 2);
265     number = height;
266     dummy = writeintbytesl(2);
267     if (left != 0 || top != 0 || width !=
268         canvasw || height != canvash) {
269         bad = 1;
270     }
271 }

```

```

272     dummy = write(x);
273     lflag = (x & 128) >> 7;
274     linterlace = (x & 64) >> 6;
275     lsort = (x & 32) >> 5;
276     lctsize = x & 7;
277
278     // local color table
279     if (lflag) {
280         nlocal = 2 << bpp;
281         lcolors = malloc_ec(nlocal);
282         if (valid(lcolors)) {
283             i = 0;
284             while (i < nlocal) {
285                 x = readintbytesl(f, 3);
286                 number = x;
287                 dummy = writeintbytesl(3);
288                 lcolors[i] = x;
289                 i = i + 1;
290             }
291         } else {
292             bad = 1;
293         }
294     }
295
296     // data sub-blocks
297     lzw = read_ec(f);
298     if (lzw < 0) {
299         bad = 1;
300     }
301     dummy = write(lzw);
302     datalen = readblocks(f, 1);
303     // decompress
304     // decode
305 }
306 }
307 } else {
308     bad = 1;
309 }
310 if (pos_ec(f) > eou || pos_ec(f) < 0) {
311     bad = 1;
312 }
313 x = seek_ec(f, eou);
314 if (x < 0) { // give up
315     finish = 1;
316 }
317 if (!bad && !finish) {
318     i = 0;
319     while (i < outidx) {
320         x = out[i];
321         print(x);
322         i = i + 1;
323     }
324 } // skip unit
325 } else { // give up
326     finish = 1;
327 }
328 }
329 x = free_ec(buffer);
330 if (!trailer) {
331     x = 59;
332     print(x);
333 }
334 return 0;
335 }

```

C.7 PCAP/DNS

PCAP files store network packets. A PCAP file contains a header and capture items. Each capture item contains 12 bytes of metadata, a 4-byte length field, and a network packet of “length” bytes. The PCAP/DNS benchmark considers only DNS packets. Specifically, each network packet of interest contains an Ethernet header, an Internet Protocol version 4 (IPv4) header, a User Datagram Protocol (UDP) header, the DNS packet, and some trailing Ethernet bytes.

The benchmark program reads a PCAP file and extracts DNS packets. For each valid DNS packet, the program prints

the source Internet Protocol (IP) address, the destination IP address, the DNS identification number, and the DNS questions and answers. When a network packet is malformed, the program discards the capture item and keeps parsing. The program rejects PCAP files with malformed headers. The program discards trailing inputs after seeing a capture item with negative length.

C.7.1 Full RIFL Version

```

1  dst_mac = malloc(6);
2  src_mac = malloc(6);
3  data = malloc(1);
4
5  func readintbytesl (f, n) { // little endian
6  x = read(f);
7  if (n == 1) {
8  return x;
9  } else {
10 y = readintbytesl(f, n-1);
11 return (y << 8) + x;
12 }
13 }
14
15 func readintbytesb (f, n) { // big endian
16 x = 0;
17 i = 0;
18 while (i < n) {
19 byte = read(f);
20 x = x << 8;
21 x = x | byte;
22 i = i + 1;
23 }
24 return x;
25 }
26
27 func parse_ethernet (f, dummy) {
28 i = 0;
29 while (i < 6) {
30 x = read(f);
31 dst_mac[i] = x;
32 i = i + 1;
33 }
34 i = 0;
35 while (i < 6) {
36 x = read(f);
37 src_mac[i] = x;
38 i = i + 1;
39 }
40
41 ether_type = readintbytesl(f, 2);
42 assert(ether_type == 8); // IPv4
43
44 dummy = parse_ipv4(f, 0);
45 return 0;
46 }
47
48 func check_sum (f, len) {
49 start = pos(f);
50 assert(len > 0 && len % 2 == 0);
51 sum = 0;
52 i = 0;
53 while (i < len / 2) {
54 x = readintbytesb(f, 2);
55 sum = sum + x;
56 i = i + 1;
57 }
58 hi = (sum >> 16) & 65535;
59 lo = sum & 65535;
60 assert(hi + lo == 65535);
61 seek(f, start);
62 return 0;
63 }
64
65 func print_ip (addr) {
66 b = (addr >> 24) & 255;
67 print(b);
68
69 b = (addr >> 16) & 255;
70 print(b);
71
72 b = (addr >> 8) & 255;
73 print(b);
74
75 b = addr & 255;
76 print(b);
77 return 0;
78 }
79
80 func parse_ipv4 (f, dummy) {
81 dummy = check_sum(f, 20); // no options
82
83 x = read(f);
84 version = (x & 240) >> 4;
85 hdr_size = x & 15;
86 x = read(f);
87 total = readintbytesb(f, 2);
88
89 id = readintbytesb(f, 2);
90 fragment = readintbytesb(f, 2);
91 dont_frag = (fragment & 16384) >> 14;
92 more_frag = (fragment & 8192) >> 13;
93 offs_frag = fragment & 8191;
94
95 ttl = read(f);
96 ip_type = read(f);
97 checksum = readintbytesb(f, 2);
98
99 src_ip = readintbytesb(f, 4);
100 dst_ip = readintbytesb(f, 4);
101
102 assert(version == 4 && hdr_size == 5 && total >=
    hdr_size * 4 && fragment & 32768 == 0 &&
    more_frag == 0 && offs_frag == 0 && ip_type
    == 17); // IPv4, no options,
    UDP
103
104 print('\n');
105 dummy = print_ip(src_ip);
106 print(' ');
107 dummy = print_ip(dst_ip);
108 print(' ');
109 dummy = parse_udp(f, total - hdr_size * 4);
110
111 return 0;
112 }
113
114 func parse_udp (f, pkt_size) {
115 src_port = readintbytesb(f, 2);
116 dst_port = readintbytesb(f, 2);
117 udp_size = readintbytesb(f, 2);
118 checksum = readintbytesb(f, 2);
119
120 assert(pkt_size <= udp_size && pkt_size > 8);
121 if (src_port == 53 || dst_port == 53) { // DNS
122 dummy = parse_dns(f, pkt_size - 8);
123 } else { // others
124 if (valid(data)) {
125 free(data);
126 }
127 data_size = pkt_size - 8;
128 data = malloc(data_size);
129 i = 0;
130 while (i < data_size) {
131 x = read(f);
132 data[i] = x;
133 i = i + 1;
134 }
135 print('\n');
136 }
137 return 0;
138 }
139
140 func parse_dns (f, data_size) {
141 id = readintbytesb(f, 2);
142 print(id);
143 print('\n');
144 flags = readintbytesb(f, 2);

```

```

145 n_q = readintbytesb(f, 2);
146 n_ans = readintbytesb(f, 2);
147 n_auth = readintbytesb(f, 2);
148 n_add = readintbytesb(f, 2);
149
150 // questions
151 i = 0;
152 while (i < n_q) {
153     stop = 0;
154     first = 1;
155     while (!stop) {
156         len = read(f);
157         if (len == 0) {
158             stop = 1;
159         } else {
160             if (first) {
161                 first = 0;
162             } else {
163                 print('.');
164             }
165             j = 0;
166             while (j < len) {
167                 x = read(f);
168                 print(x);
169                 j = j + 1;
170             }
171         }
172     }
173     print('\n');
174     type_q = readintbytesb(f, 2);
175     class_q = readintbytesb(f, 2);
176     i = i + 1;
177 }
178
179 // answers
180 i = 0;
181 while (i < n_ans) {
182     ptr = readintbytesb(f, 2);
183     assert(ptr == 49164);
184     type_ans = readintbytesb(f, 2);
185     class_ans = readintbytesb(f, 2);
186     ttl = readintbytesb(f, 4);
187     len = readintbytesb(f, 2);
188     if (type_ans == 1) {
189         assert(len == 4);
190         addr = readintbytesb(f, 4);
191         dummy = print_ip(addr);
192     } else {
193         assert(type_ans == 5);
194         j = 0;
195         while (j < len) {
196             x = read(f);
197             print(x);
198             j = j + 1;
199         }
200     }
201     print('\n');
202     i = i + 1;
203 }
204
205 // authority
206 // additional
207 return 0;
208 }
209
210 main {
211     f = openb("../inputs/pcap/bad.pcap", 1);
212
213     x = read(f);
214     assert(x == 212);
215     x = read(f);
216     assert(x == 195);
217     x = read(f);
218     assert(x == 178);
219     x = read(f);
220     assert(x == 161);
221     maj_ver = readintbytesl(f, 2);
222     min_ver = readintbytesl(f, 2);
223     this_zone = readintbytesl(f, 4);
224     sigfigs = readintbytesl(f, 4);

```

```

225     snap_len = readintbytesl(f, 4); // number of
226         packets
227     link_type = readintbytesl(f, 4);
228     assert(link_type == 1); // ethernet
229
230     inspectb (1, f, 12, 4, 0) {
231         ts_epoch = readintbytesl(f, 4);
232         ts_nanosec = readintbytesl(f, 4);
233         caplen = readintbytesl(f, 4);
234         length = readintbytesl(f, 4);
235         assert(caplen == length);
236
237         dummy = parse_ethernet(f, 0);
238     }
239     return 0;
240 }

```

C.7.2 Explicit Check Version

```

1 dst_mac = malloc_ec(6);
2 src_mac = malloc_ec(6);
3 data = malloc_ec(1);
4
5 func readintbytesl (f, n) { // little endian
6     x = read_ec(f);
7     assert(x >= 0);
8     if (n == 1) {
9         return x;
10    } else {
11        y = readintbytesl(f, n-1);
12        return (y << 8) + x;
13    }
14 }
15
16 func readintbytesb (f, n) { // big endian
17     x = 0;
18     i = 0;
19     while (i < n) {
20         byte = read_ec(f);
21         assert(byte >= 0);
22         x = x << 8;
23         x = x | byte;
24         i = i + 1;
25     }
26     return x;
27 }
28
29 func parse_ethernet (f, dummy) {
30     i = 0;
31     while (i < 6) {
32         x = read_ec(f);
33         assert(x >= 0);
34         dst_mac[i] = x;
35         i = i + 1;
36     }
37     i = 0;
38     while (i < 6) {
39         x = read_ec(f);
40         assert(x >= 0);
41         src_mac[i] = x;
42         i = i + 1;
43     }
44
45     ether_type = readintbytesl(f, 2);
46     assert(ether_type == 8); // IPv4
47
48     dummy = parse_ipv4(f, 0);
49     return 0;
50 }
51
52 func check_sum (f, len) {
53     start = pos_ec(f);
54     assert(len > 0 && len % 2 == 0 && start >= 0);
55     sum = 0;
56     i = 0;
57     while (i < len / 2) {
58         x = readintbytesb(f, 2);
59         sum = sum + x;
60         i = i + 1;
61     }

```

```

62     hi = (sum >> 16) & 65535;
63     lo = sum & 65535;
64     x = seek_ec(f, start);
65     assert(hi + lo == 65535 && x >= 0);
66     return 0;
67 }
68
69 func print_ip (addr) {
70     b = (addr >> 24) & 255;
71     print(b);
72     print('.');
73     b = (addr >> 16) & 255;
74     print(b);
75     print('.');
76     b = (addr >> 8) & 255;
77     print(b);
78     print('.');
79     b = addr & 255;
80     print(b);
81     return 0;
82 }
83
84 func parse_ipv4 (f, dummy) {
85     dummy = check_sum(f, 20); // no options
86
87     x = read_ec(f);
88     assert(x >= 0);
89     version = (x & 240) >> 4;
90     hdr_size = x & 15;
91     x = read_ec(f);
92     assert(x >= 0);
93     total = readintbytesb(f, 2);
94
95     id = readintbytesb(f, 2);
96     fragment = readintbytesb(f, 2);
97     dont_frag = (fragment & 16384) >> 14;
98     more_frag = (fragment & 8192) >> 13;
99     offs_frag = fragment & 8191;
100
101     ttl = read_ec(f);
102     ip_type = read_ec(f);
103     checksum = readintbytesb(f, 2);
104
105     src_ip = readintbytesb(f, 4);
106     dst_ip = readintbytesb(f, 4);
107
108     assert(version == 4 && hdr_size == 5 && total >=
109             hdr_size * 4 && fragment & 32768 == 0 &&
110             more_frag == 0 && offs_frag == 0 && ttl >=
111             0 && ip_type == 17); // IPv4, no options,
112             UDP
113
114     print('\n');
115     dummy = print_ip(src_ip);
116     print(' ');
117     dummy = print_ip(dst_ip);
118     print(' ');
119     dummy = parse_udp(f, total - hdr_size * 4);
120
121     return 0;
122 }
123
124 func parse_udp (f, pkt_size) {
125     src_port = readintbytesb(f, 2);
126     dst_port = readintbytesb(f, 2);
127     udp_size = readintbytesb(f, 2);
128     checksum = readintbytesb(f, 2);
129
130     assert(pkt_size <= udp_size && pkt_size > 8);
131     if (src_port == 53 || dst_port == 53) { // DNS
132         dummy = parse_dns(f, pkt_size - 8);
133     } else { // others
134         if (valid(data)) {
135             dummy = free_ec(data);
136         }
137         data_size = pkt_size - 8;
138         data = malloc_ec(data_size);
139         assert(valid(data));
140         i = 0;
141         while (i < data_size) {
142             x = read_ec(f);
143             assert(x >= 0);
144             data[i] = x;
145             i = i + 1;
146         }
147         print('\n');
148     }
149     return 0;
150 }
151
152 func parse_dns (f, data_size) {
153     id = readintbytesb(f, 2);
154     print(id);
155     print('\n');
156     flags = readintbytesb(f, 2);
157     n_q = readintbytesb(f, 2);
158     n_ans = readintbytesb(f, 2);
159     n_auth = readintbytesb(f, 2);
160     n_add = readintbytesb(f, 2);
161
162     // questions
163     i = 0;
164     while (i < n_q) {
165         stop = 0;
166         first = 1;
167         while (!stop) {
168             len = read_ec(f);
169             assert(len >= 0);
170             if (len == 0) {
171                 stop = 1;
172             } else {
173                 if (first) {
174                     first = 0;
175                 } else {
176                     print('.');
177                 }
178                 j = 0;
179                 while (j < len) {
180                     x = read_ec(f);
181                     assert(x >= 0);
182                     print(x);
183                     j = j + 1;
184                 }
185             }
186         }
187         print('\n');
188         type_q = readintbytesb(f, 2);
189         class_q = readintbytesb(f, 2);
190         i = i + 1;
191     }
192
193     // answers
194     i = 0;
195     while (i < n_ans) {
196         ptr = readintbytesb(f, 2);
197         assert(ptr == 49164);
198         type_ans = readintbytesb(f, 2);
199         class_ans = readintbytesb(f, 2);
200         ttl = readintbytesb(f, 4);
201         len = readintbytesb(f, 2);
202         if (type_ans == 1) {
203             assert(len == 4);
204             addr = readintbytesb(f, 4);
205             dummy = print_ip(addr);
206         } else {
207             assert(type_ans == 5 && len > 0);
208             j = 0;
209             while (j < len) {
210                 x = read_ec(f);
211                 assert(x >= 0);
212                 print(x);
213                 j = j + 1;
214             }
215         }
216         print('\n');
217         i = i + 1;
218     }
219
220     // authority
221     // additional
222     return 0;
223 }

```

```

220
221 main {
222     assert(valid(dst_mac) && valid(src_mac) && valid
           (data));
223     f = openb_ec("../inputs/pcap/bad.pcap", 1);
224     assert(valid(f));
225
226     x = read_ec(f);
227     assert(x == 212);
228     x = read_ec(f);
229     assert(x == 195);
230     x = read_ec(f);
231     assert(x == 178);
232     x = read_ec(f);
233     assert(x == 161);
234     maj_ver = readintbytesl(f, 2);
235     min_ver = readintbytesl(f, 2);
236     this_zone = readintbytesl(f, 4);
237     sigfigs = readintbytesl(f, 4);
238     snap_len = readintbytesl(f, 4); // number of
           packets
239     link_type = readintbytesl(f, 4);
240     assert(link_type == 1); // ethernet
241
242     inspectb (1, f, 12, 4, 0) {
243         ts_epoch = readintbytesl(f, 4);
244         ts_nanosec = readintbytesl(f, 4);
245         caplen = readintbytesl(f, 4);
246         length = readintbytesl(f, 4);
247         assert(caplen == length);
248
249         dummy = parse_ethernet(f, 0);
250     }
251
252     return 0;
253 }

```

C.7.3 Explicit Recovery Version

```

1  dst_mac = malloc_ec(6);
2  src_mac = malloc_ec(6);
3  dst_ip = 0;
4  src_ip = 0;
5  data = malloc_ec(1);
6
7  bad = 0;
8  idx = 0;
9  out = malloc_ec(1000);
10
11 func readintbytesl (f, n) { // little endian
12     x = read_ec(f);
13     if (x < 0) {
14         bad = 1;
15         return -1;
16     }
17     if (n == 1) {
18         return x;
19     } else {
20         y = readintbytesl(f, n-1);
21         return (y << 8) + x;
22     }
23 }
24
25 func readintbytesb (f, n) { // big endian
26     x = 0;
27     i = 0;
28     while (i < n) {
29         byte = read_ec(f);
30         if (byte < 0) {
31             bad = 1;
32             return -1;
33         }
34         x = x << 8;
35         x = x | byte;
36         i = i + 1;
37     }
38     return x;
39 }
40
41 func parse_ethernet (f, dummy) {
42     i = 0;

```

```

43     while (i < 6) {
44         x = read_ec(f);
45         if (x < 0) {
46             bad = 1;
47             return -1;
48         }
49         dst_mac[i] = x;
50         i = i + 1;
51     }
52     i = 0;
53     while (i < 6) {
54         x = read_ec(f);
55         if (x < 0) {
56             bad = 1;
57             return -1;
58         }
59         src_mac[i] = x;
60         i = i + 1;
61     }
62
63     ether_type = readintbytesl(f, 2);
64     if (bad || ether_type != 8) {
65         bad = 1;
66         return -1;
67     } // IPv4
68     dummy = parse_ipv4(f, 0);
69     return 0;
70 }
71
72 func check_sum (f, len) {
73     start = pos_ec(f);
74     if (len <= 0 || len % 2 != 0 || start < 0) {
75         bad = 1;
76         return -1;
77     }
78     sum = 0;
79     i = 0;
80     while (i < len / 2) {
81         x = readintbytesb(f, 2);
82         sum = sum + x;
83         i = i + 1;
84     }
85     hi = (sum >> 16) & 65535;
86     lo = sum & 65535;
87     x = seek_ec(f, start);
88     if (hi + lo != 65535 || x < 0) {
89         bad = 1;
90         return -1;
91     }
92     return 0;
93 }
94
95 func prtbuf (x) {
96     if (idx >= 1000) {
97         bad = 1;
98         return -1;
99     }
100    out[idx] = x;
101    idx = idx + 1;
102    return 0;
103 }
104
105 func prtbuf_ip (addr) {
106    dummy = prtbuf((addr >> 24) & 255);
107    dummy = prtbuf('.');
108    dummy = prtbuf((addr >> 16) & 255);
109    dummy = prtbuf('.');
110    dummy = prtbuf((addr >> 8) & 255);
111    dummy = prtbuf('.');
112    dummy = prtbuf(addr & 255);
113    return 0;
114 }
115
116 func parse_ipv4 (f, dummy) {
117    dummy = check_sum(f, 20); // no options
118    if (bad) {
119        return -1;
120    }
121
122    x = read_ec(f);
123    if (x < 0) {

```

```

124     bad = 1;
125     return -1;
126 }
127 version = (x & 240) >> 4;
128 hdr_size = x & 15;
129 x = read_ec(f);
130 if (x < 0) {
131     bad = 1;
132     return -1;
133 }
134 total = readintbytesb(f, 2);
135
136 id = readintbytesb(f, 2);
137 fragment = readintbytesb(f, 2);
138 dont_frag = (fragment & 16384) >> 14;
139 more_frag = (fragment & 8192) >> 13;
140 offs_frag = fragment & 8191;
141
142 ttl = read_ec(f);
143 ip_type = read_ec(f);
144 checksum = readintbytesb(f, 2);
145
146 src_ip = readintbytesb(f, 4);
147 dst_ip = readintbytesb(f, 4);
148
149 if (bad || version != 4 || hdr_size != 5 ||
    total < hdr_size * 4 || fragment & 32768 !=
    0 || more_frag != 0 || offs_frag != 0 ||
    ttl < 0 || ip_type != 17) { // IPv4, no
    options, UDP
150     bad = 1;
151     return -1;
152 }
153 dummy = prtbuf('\n');
154 dummy = prtbuf_ip(src_ip);
155 dummy = prtbuf(' ');
156 dummy = prtbuf_ip(dst_ip);
157 dummy = prtbuf(' ');
158 dummy = parse_udp(f, total - hdr_size * 4);
159 return 0;
160 }
161
162 func parse_udp (f, pkt_size) {
163     src_port = readintbytesb(f, 2);
164     dst_port = readintbytesb(f, 2);
165     udp_size = readintbytesb(f, 2);
166     checksum = readintbytesb(f, 2);
167
168     if (bad || pkt_size > udp_size || pkt_size <= 8)
169     {
170         bad = 1;
171         return -1;
172     }
173     if (src_port == 53 || dst_port == 53) { // DNS
174         dummy = parse_dns(f, pkt_size - 8);
175     } else { // others
176         if (valid(data)) {
177             dummy = free_ec(data);
178         }
179         data_size = pkt_size - 8;
180         data = malloc_ec(data_size);
181         if (!valid(data)) {
182             bad = 1;
183             return -1;
184         }
185         i = 0;
186         while (i < data_size) {
187             x = read_ec(f);
188             if (x < 0) {
189                 bad = 1;
190                 return -1;
191             }
192             data[i] = x;
193             i = i + 1;
194         }
195         dummy = prtbuf('\n');
196     }
197     return 0;
198 }
199
200 func parse_dns (f, data_size) {
201     id = readintbytesb(f, 2);
202     dummy = prtbuf(id);
203     dummy = prtbuf('\n');
204     flags = readintbytesb(f, 2);
205     n_q = readintbytesb(f, 2);
206     n_ans = readintbytesb(f, 2);
207     n_auth = readintbytesb(f, 2);
208     n_add = readintbytesb(f, 2);
209
210     // questions
211     i = 0;
212     while (i < n_q) {
213         stop = 0;
214         first = 1;
215         while (!stop) {
216             len = read_ec(f);
217             if (len < 0) {
218                 bad = 1;
219                 return -1;
220             }
221             if (len == 0) {
222                 stop = 1;
223             } else {
224                 if (first) {
225                     first = 0;
226                 } else {
227                     dummy = prtbuf('.');
228                 }
229                 j = 0;
230                 while (j < len) {
231                     x = read_ec(f);
232                     if (x < 0 || idx >= 1000) {
233                         bad = 1;
234                         return -1;
235                     }
236                     out[idx] = x;
237                     j = j + 1;
238                     idx = idx + 1;
239                 }
240             }
241         }
242         dummy = prtbuf('\n');
243         type_q = readintbytesb(f, 2);
244         class_q = readintbytesb(f, 2);
245         i = i + 1;
246     }
247
248     // answers
249     i = 0;
250     while (i < n_ans) {
251         ptr = readintbytesb(f, 2);
252         if (ptr != 49164) {
253             bad = 1;
254             return -1;
255         }
256         type_ans = readintbytesb(f, 2);
257         class_ans = readintbytesb(f, 2);
258         ttl = readintbytesb(f, 4);
259         len = readintbytesb(f, 2);
260         if (type_ans == 1) {
261             if (len != 4) {
262                 bad = 1;
263                 return -1;
264             }
265             addr = readintbytesb(f, 4);
266             dummy = prtbuf_ip(addr);
267         } else {
268             if (type_ans != 5 || len <= 0) {
269                 bad = 1;
270                 return -1;
271             }
272             j = 0;
273             while (j < len) {
274                 x = read_ec(f);
275                 if (x < 0 || idx >= 1000) {
276                     bad = 1;
277                     return -1;
278                 }
279                 out[idx] = x;
280                 j = j + 1;

```

```

281     idx = idx + 1;
282     }
283 }
284 dummy = prtbuf('\n');
285 i = i + 1;
286 }
287
288 // authority
289 // additional
290 return 0;
291 }
292
293 main {
294     if (!valid(dst_mac) || !valid(src_mac) || !valid
295         (data) || !valid(out)) {
296         exit(1);
297     }
298     f = openb_ec("../inputs/pcap/bad.pcap", 1);
299     if (!valid(f)) {
300         exit(1);
301     }
302     x = read_ec(f);
303     if (x != 212) {
304         exit(1);
305     }
306     x = read_ec(f);
307     if (x != 195) {
308         exit(1);
309     }
310     x = read_ec(f);
311     if (x != 178) {
312         exit(1);
313     }
314     x = read_ec(f);
315     if (x != 161) {
316         exit(1);
317     }
318     maj_ver = readintbytesl(f, 2);
319     min_ver = readintbytesl(f, 2);
320     this_zone = readintbytesl(f, 4);
321     sigfigs = readintbytesl(f, 4);
322     snap_len = readintbytesl(f, 4); // number of
323         packets
324     link_type = readintbytesl(f, 4);
325     if (bad || link_type != 1) {
326         exit(1);
327     } // ethernet
328     lookatb (1, f, 12, 4, 0) {
329         bad = 0;
330         idx = 0;
331         ts_epoch = readintbytesl(f, 4);
332         ts_nanosec = readintbytesl(f, 4);
333         caplen = readintbytesl(f, 4);
334         length = readintbytesl(f, 4);
335         if (!bad && caplen == length) {
336             dummy = parse_ethernet(f, 0);
337             if (!bad) {
338                 i = 0;
339                 while (i < idx) {
340                     x = out[i];
341                     print(x);
342                     i = i + 1;
343                 }
344             }
345         } // skip unit
346     }
347
348     return 0;
349 }

```

C.7.4 Conventional Version

```

1 dst_mac = malloc_ec(6);
2 src_mac = malloc_ec(6);
3 dst_ip = 0;
4 src_ip = 0;
5 data = malloc_ec(1);
6
7 bad = 0;

```

```

8 idx = 0;
9 out = malloc_ec(1000);
10
11 func readintbytesl (f, n) { // little endian
12     x = read_ec(f);
13     if (x < 0) {
14         bad = 1;
15         return -1;
16     }
17     if (n == 1) {
18         return x;
19     } else {
20         y = readintbytesl(f, n-1);
21         return (y << 8) + x;
22     }
23 }
24
25 func readintbytesb (f, n) { // big endian
26     x = 0;
27     i = 0;
28     while (i < n) {
29         byte = read_ec(f);
30         if (byte < 0) {
31             bad = 1;
32             return -1;
33         }
34         x = x << 8;
35         x = x | byte;
36         i = i + 1;
37     }
38     return x;
39 }
40
41 func parse_ethernet (f, dummy) {
42     i = 0;
43     while (i < 6) {
44         x = read_ec(f);
45         if (x < 0) {
46             bad = 1;
47             return -1;
48         }
49         dst_mac[i] = x;
50         i = i + 1;
51     }
52     i = 0;
53     while (i < 6) {
54         x = read_ec(f);
55         if (x < 0) {
56             bad = 1;
57             return -1;
58         }
59         src_mac[i] = x;
60         i = i + 1;
61     }
62
63     ether_type = readintbytesl(f, 2);
64     if (bad || ether_type != 8) {
65         bad = 1;
66         return -1;
67     } // IPv4
68     dummy = parse_ipv4(f, 0);
69     return 0;
70 }
71
72 func check_sum (f, len) {
73     start = pos_ec(f);
74     if (len <= 0 || len % 2 != 0 || start < 0) {
75         bad = 1;
76         return -1;
77     }
78     sum = 0;
79     i = 0;
80     while (i < len / 2) {
81         x = readintbytesb(f, 2);
82         sum = sum + x;
83         i = i + 1;
84     }
85     hi = (sum >> 16) & 65535;
86     lo = sum & 65535;
87     x = seek_ec(f, start);
88     if (hi + lo != 65535 || x < 0) {

```

```

89     bad = 1;
90     return -1;
91 }
92 return 0;
93 }
94
95 func prtbuf (x) {
96     if (idx >= 1000) {
97         bad = 1;
98         return -1;
99     }
100    out[idx] = x;
101    idx = idx + 1;
102    return 0;
103 }
104
105 func prtbuf_ip (addr) {
106    dummy = prtbuf((addr >> 24) & 255);
107    dummy = prtbuf('.');
108    dummy = prtbuf((addr >> 16) & 255);
109    dummy = prtbuf('.');
110    dummy = prtbuf((addr >> 8) & 255);
111    dummy = prtbuf('.');
112    dummy = prtbuf(addr & 255);
113    return 0;
114 }
115
116 func parse_ipv4 (f, dummy) {
117    dummy = check_sum(f, 20); // no options
118    if (bad) {
119        return -1;
120    }
121
122    x = read_ec(f);
123    if (x < 0) {
124        bad = 1;
125        return -1;
126    }
127    version = (x & 240) >> 4;
128    hdr_size = x & 15;
129    x = read_ec(f);
130    if (x < 0) {
131        bad = 1;
132        return -1;
133    }
134    total = readintbytesb(f, 2);
135
136    id = readintbytesb(f, 2);
137    fragment = readintbytesb(f, 2);
138    dont_frag = (fragment & 16384) >> 14;
139    more_frag = (fragment & 8192) >> 13;
140    offs_frag = fragment & 8191;
141
142    ttl = read_ec(f);
143    ip_type = read_ec(f);
144    checksum = readintbytesb(f, 2);
145
146    src_ip = readintbytesb(f, 4);
147    dst_ip = readintbytesb(f, 4);
148
149    if (bad || version != 4 || hdr_size != 5 ||
150        total < hdr_size * 4 || fragment & 32768 !=
151        0 || more_frag != 0 || offs_frag != 0 ||
152        ttl < 0 || ip_type != 17) { // IPv4, no
153        options, UDP
154        bad = 1;
155        return -1;
156    }
157    dummy = prtbuf('\n');
158    dummy = prtbuf_ip(src_ip);
159    dummy = prtbuf(' ');
160    dummy = prtbuf_ip(dst_ip);
161    dummy = prtbuf(' ');
162    dummy = parse_udp(f, total - hdr_size * 4);
163    return 0;
164 }
165
166 func parse_udp (f, pkt_size) {
167    src_port = readintbytesb(f, 2);
168    dst_port = readintbytesb(f, 2);
169    udp_size = readintbytesb(f, 2);
170
171    checksum = readintbytesb(f, 2);
172
173    if (bad || pkt_size > udp_size || pkt_size <= 8)
174    {
175        bad = 1;
176        return -1;
177    }
178
179    if (src_port == 53 || dst_port == 53) { // DNS
180        dummy = parse_dns(f, pkt_size - 8);
181    } else { // others
182        if (valid(data)) {
183            dummy = free_ec(data);
184        }
185        data_size = pkt_size - 8;
186        data = malloc_ec(data_size);
187        if (!valid(data)) {
188            bad = 1;
189            return -1;
190        }
191        i = 0;
192        while (i < data_size) {
193            x = read_ec(f);
194            if (x < 0) {
195                bad = 1;
196                return -1;
197            }
198            data[i] = x;
199            i = i + 1;
200        }
201        dummy = prtbuf('\n');
202    }
203    return 0;
204 }
205
206 func parse_dns (f, data_size) {
207    id = readintbytesb(f, 2);
208    dummy = prtbuf(id);
209    dummy = prtbuf('\n');
210    flags = readintbytesb(f, 2);
211    n_q = readintbytesb(f, 2);
212    n_ans = readintbytesb(f, 2);
213    n_auth = readintbytesb(f, 2);
214    n_add = readintbytesb(f, 2);
215
216    // questions
217    i = 0;
218    while (i < n_q) {
219        stop = 0;
220        first = 1;
221        while (!stop) {
222            len = read_ec(f);
223            if (len < 0) {
224                bad = 1;
225                return -1;
226            }
227            if (len == 0) {
228                stop = 1;
229            } else {
230                if (first) {
231                    first = 0;
232                } else {
233                    dummy = prtbuf('.');
234                }
235                j = 0;
236                while (j < len) {
237                    x = read_ec(f);
238                    if (x < 0 || idx >= 1000) {
239                        bad = 1;
240                        return -1;
241                    }
242                    out[idx] = x;
243                    j = j + 1;
244                    idx = idx + 1;
245                }
246            }
247            i = i + 1;
248        }
249        dummy = prtbuf('\n');
250        type_q = readintbytesb(f, 2);
251        class_q = readintbytesb(f, 2);
252        i = i + 1;

```



```

246 }
247
248 // answers
249 i = 0;
250 while (i < n_ans) {
251     ptr = readintbytesb(f, 2);
252     if (ptr != 49164) {
253         bad = 1;
254         return -1;
255     }
256     type_ans = readintbytesb(f, 2);
257     class_ans = readintbytesb(f, 2);
258     ttl = readintbytesb(f, 4);
259     len = readintbytesb(f, 2);
260     if (type_ans == 1) {
261         if (len != 4) {
262             bad = 1;
263             return -1;
264         }
265         addr = readintbytesb(f, 4);
266         dummy = prtbuf_ip(addr);
267     } else {
268         if (type_ans != 5 || len <= 0) {
269             bad = 1;
270             return -1;
271         }
272         j = 0;
273         while (j < len) {
274             x = read_ec(f);
275             if (x < 0 || idx >= 1000) {
276                 bad = 1;
277                 return -1;
278             }
279             out[idx] = x;
280             j = j + 1;
281             idx = idx + 1;
282         }
283     }
284     dummy = prtbuf('\n');
285     i = i + 1;
286 }
287
288 // authority
289 // additional
290 return 0;
291 }
292
293 main {
294     if (!valid(dst_mac) || !valid(src_mac) || !valid
295         (data) || !valid(out)) {
296         exit(1);
297     }
298     f = openb_ec("../inputs/pcap/bad.pcap", 1);
299     if (!valid(f)) {
300         exit(1);
301     }
302     x = read_ec(f);
303     if (x != 212) {
304         exit(1);
305     }
306     x = read_ec(f);
307     if (x != 195) {
308         exit(1);
309     }
310     x = read_ec(f);
311     if (x != 178) {
312         exit(1);
313     }
314     x = read_ec(f);
315     if (x != 161) {
316         exit(1);
317     }
318     maj_ver = readintbytesl(f, 2);
319     min_ver = readintbytesl(f, 2);
320     this_zone = readintbytesl(f, 4);
321     sigfigs = readintbytesl(f, 4);
322     snap_len = readintbytesl(f, 4); // number of
323         packets
324     link_type = readintbytesl(f, 4);
325     if (bad || link_type != 1) {

```

```

325     exit(1);
326 } // ethernet
327
328 finish = 0;
329 while (!finish) {
330     bad = 0;
331     idx = 0;
332     ts_epoch = readintbytesl(f, 4);
333     ts_nanosec = readintbytesl(f, 4);
334     caplen = readintbytesl(f, 4);
335     length = readintbytesl(f, 4);
336     if (!bad && length >= 0) {
337         eou = pos_ec(f) + length;
338         if (!bad && caplen == length) {
339             dummy = parse_ethernet(f, 0);
340             if (pos_ec(f) < 0 || pos_ec(f) > eou) {
341                 bad = 1;
342             }
343             if (!bad) {
344                 i = 0;
345                 while (i < idx) {
346                     x = out[i];
347                     print(x);
348                     i = i + 1;
349                 }
350             }
351         } // skip unit
352         x = seek_ec(f, eou);
353         if (x < 0) {
354             finish = 1;
355         }
356     } else { // give up
357         finish = 1;
358     }
359 }
360
361 return 0;
362 }

```

D. Extending RIFL for Handling Errors Explicitly

For evaluation, we extend RIFL to support handling errors explicitly. In general, however, we recommend developers to use only the core language features that handle errors implicitly.

We extend RIFL to support look-at loops. A look-at loop iterates through the inputs as an inspect loop does, except that the look-at loop does not attempt to detect or recover from errors. Figures 21 and 22 present the semantics for look-at loops for text input files, using the same helper functions as for Figures 12 and 13. Figures 23 and 24 present the semantics for look-at loops for binary input files, using the same helper functions as for Figures 14 and 15.

We also extend RIFL to support an additional set of system calls for file and memory operations. These extensions resemble the core RIFL system calls when there are no errors, but return explicit error codes instead of triggering error recovery when there are errors. Table 11 presents the error-code extensions for core RIFL system calls. The two columns present the system calls in the core RIFL language (Core-language interface) and in the extended language (Error-code extension), respectively. Each row contains the two versions of a system call. Figures 25–28 present the semantics for these error-code system calls.

To support these error-code extensions, we extend RIFL with the `valid` predicate that tests whether a file variable is not null. Figure 29 presents the semantics for the `valid`

$\frac{\sigma_S(f) = \text{null}}{\langle \text{lookatb}(e, f, d_u, d_s)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle}$	(lookb-null)
$\frac{\sigma_S(f) \neq \text{null} \quad \sigma = \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \quad \langle e, \sigma \rangle \Downarrow_e \text{err} \vee \langle o, \sigma \rangle \Downarrow_e \text{err} \vee \langle w, \sigma \rangle \Downarrow_e \text{err} \vee \langle c, \sigma \rangle \Downarrow_e \text{err}}{\langle \text{lookatb}(e, f, o, w, c)\{s\}, \sigma \rangle \Downarrow_s \langle \sigma, \text{bad} \rangle}$	(lookb-bad)
$\frac{\sigma_S(f) \neq \text{null} \quad \sigma = \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \quad \langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle o, \sigma \rangle \Downarrow_e u_o \quad \langle w, \sigma \rangle \Downarrow_e u_w \quad \langle c, \sigma \rangle \Downarrow_e u_c \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{cut} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u_o < 0 \vee u_w < 0 \vee u_c < 0}{\langle \text{lookatb}(e, f, o, w, c)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle}$	(lookb-neg)
$\frac{\sigma_S(f) \neq \text{null} \quad \sigma = \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \quad \langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle o, \sigma \rangle \Downarrow_e u_o \quad \langle w, \sigma \rangle \Downarrow_e u_w \quad \langle c, \sigma \rangle \Downarrow_e u_c \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{cut} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u_o \geq 0 \quad u_w \geq 0 \quad \text{parseint}(l + u_o, u_w) = v \quad v \geq 0 \quad u_c \geq 0 \quad l + u_o + u_w + v + u_c = \text{cut}' \quad \text{cut}' > \text{cut}}{\langle \text{lookatb}(e, f, o, w, c)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle, \text{bad} \rangle}$	(lookb-large)
$\frac{\sigma_S(F) \neq \text{null} \quad \sigma = \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \quad \langle e, \sigma \rangle \Downarrow_e \text{true} \quad \langle o, \sigma \rangle \Downarrow_e u_o \quad \langle w, \sigma \rangle \Downarrow_e u_w \quad \langle c, \sigma \rangle \Downarrow_e u_c \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{cut} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u_o \geq 0 \quad u_w \geq 0 \quad \text{parseint}(l + u_o, u_w) = v \quad v \geq 0 \quad u_c \geq 0 \quad l + u_o + u_w + v + u_c = \text{cut}' \quad l < \text{cut}' \leq \text{cut} \quad \langle s, \langle \sigma_S, \sigma_H, \sigma_F[\sigma_S(f)] \mapsto \langle \text{str}, l, l, \text{cut}' \rangle \rangle, \sigma_D \rangle \rangle \Downarrow_s \langle \sigma', \text{bad} \rangle}{\langle \text{lookatb}(e, f, o, w, c)\{s\}, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \sigma', \text{bad} \rangle}$	(lookb-abort)

Figure 24: Semantics for iterators without error handling—with bad binary inputs

$\frac{\langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{err}}{\langle a = \text{malloc_ec}(e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[a \mapsto \text{null}], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(malloc-ec-bad)
$\frac{\langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad u \leq 0}{\langle a = \text{malloc_ec}(e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[a \mapsto \text{null}], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(malloc-ec-neg)
$\frac{\langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad u > 0 \quad \text{heap allocate}(u) = \perp}{\langle a = \text{malloc_ec}(e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[a \mapsto \text{null}], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(malloc-ec-ovf)
$\frac{\langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad u > 0 \quad \text{heap allocate}(u) = \text{addr}}{\langle a = \text{malloc_ec}(e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[a \mapsto \text{addr}], \sigma_H[\text{addr} \mapsto \langle [0 \mapsto 0, 1 \mapsto 0, \dots, u-1 \mapsto 0], u \rangle], \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(malloc-ec-ok)
$\frac{\sigma_S(a) = \text{null}}{\langle x = \text{free_ec}(a), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto -1], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(free-ec-null)
$\frac{\sigma_S(a) \neq \text{null}}{\langle x = \text{free_ec}(a), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto 0, a \mapsto \text{null}], \sigma_H[\sigma_S(a) \mapsto \perp], \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(free-ec-ok)

Figure 25: Semantics for arrays with error codes

$\frac{\text{file } \text{str} \text{ does not exist}}{\langle f = \text{opent_ec}(\text{str}), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[f \mapsto \text{null}], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(opent-ec-bad)
$\frac{\text{file } \text{str} \text{ exists}}{\langle f = \text{opent_ec}(\text{str}), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[f \mapsto \text{hndl}], \sigma_H, \sigma_F[\text{hndl} \mapsto \langle \text{str}, 0, 0, \langle \emptyset, \emptyset, \emptyset \rangle] \rangle], \sigma_D \rangle, \text{ok} \rangle}$	(opent-ec-ok)
$\frac{\text{file } \text{str} \text{ does not exist}}{\langle f = \text{openb_ec}(\text{str}), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[f \mapsto \text{null}], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(openb-ec-bad)
$\frac{\text{file } \text{str} \text{ exists} \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle}{\langle f = \text{openb_ec}(\text{str}), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[f \mapsto \text{hndl}], \sigma_H, \sigma_F[\text{hndl} \mapsto \langle \text{str}, 0, 0, n \rangle], \sigma_D \rangle, \text{ok} \rangle}$	(openb-ec-ok)

Figure 27: Semantics for opening input files with error codes

$\frac{\sigma_S(f) = \text{null}}{\langle x = \text{seek_ec}(f, e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto -1], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(sk-ec-null)
$\frac{\sigma_S(f) \neq \text{null} \quad \langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{err}}{\langle x = \text{seek_ec}(f, e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto -1], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(sk-ec-bad)
$\frac{\sigma_S(f) \neq \text{null} \quad \langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad u < \text{sou}}{\langle x = \text{seek_ec}(f, e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto -1], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(sk-ec-l)
$\frac{\sigma_S(f) \neq \text{null} \quad \langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad \text{sou} \leq u \leq \Lambda(l)}{\langle x = \text{seek_ec}(f, e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto u], \sigma_H, \sigma_F[\sigma_S(f) \mapsto \langle \text{str}, u, \text{sou}, \text{ud} \rangle], \sigma_D \rangle, \text{ok} \rangle}$	(sk-ec-ok)
$\frac{\sigma_S(f) \neq \text{null} \quad \langle e, \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e u \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad u > \Lambda(l)}{\langle x = \text{seek_ec}(f, e), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto -1], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(sk-ec-r)
$\frac{\sigma_S(f) = \text{null}}{\langle x = \text{read_ec}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto -1], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(frd-ec-null)
$\frac{\sigma_S(f) \neq \text{null} \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad l = \Lambda(l)}{\langle x = \text{read_ec}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto -1], \sigma_H, \sigma_F, \sigma_D \rangle, \text{ok} \rangle}$	(frd-ec-out)
$\frac{\sigma_S(f) \neq \text{null} \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad l < \Lambda(l)}{\langle x = \text{read_ec}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_s \langle \langle \sigma_S[x \mapsto \gamma(l)], \sigma_H, \sigma_F[\sigma_S(f) \mapsto \langle \text{str}, l + 1, \text{ud} \rangle], \sigma_D \rangle, \text{ok} \rangle}$	(frd-ec-ok)

Figure 28: Semantics for accessing input files with error codes

$\frac{\sigma_S(f) = \text{null}}{\langle \text{end_ec}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e -1}$	(end-ec-null)
$\frac{\sigma_S(f) \neq \text{null} \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad l = \Lambda(l)}{\langle \text{end_ec}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{true}}$	(end-ec-t)
$\frac{\sigma_S(f) \neq \text{null} \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle \quad \sigma_D(\text{str}) = \langle \gamma, n \rangle \quad l < \Lambda(l)}{\langle \text{end_ec}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{false}}$	(end-ec-f)
$\frac{\sigma_S(f) = \text{null}}{\langle \text{pos_ec}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e -1}$	(pos-ec-null)
$\frac{\sigma_S(f) \neq \text{null} \quad \sigma_F(\sigma_S(f)) = \langle \text{str}, l, \text{sou}, \text{ud} \rangle}{\langle \text{pos_ec}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e l}$	(pos-ec-ok)

Figure 26: Semantics for input file expressions with error codes

$\frac{\sigma_S(f) \neq \text{null}}{\langle \text{valid}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{true}}$	(fvalid-t)
$\frac{\sigma_S(f) = \text{null}}{\langle \text{valid}(f), \langle \sigma_S, \sigma_H, \sigma_F, \sigma_D \rangle \rangle \Downarrow_e \text{false}}$	(fvalid-f)

Figure 29: Semantics for expressions to support error-code extensions

predicate. In addition, the rules for `inspectt`, `inspectb`, `end`, `pos`, `seek`, and `read` should also consider the new situation where $\sigma_S(f) = \text{null}$.

Table 11: Error-code interfaces for system calls

Core-language interface	Error-code extension
<code>a = malloc(e)</code>	<code>a = malloc_ec(e)</code>
<code>free(a)</code>	<code>x = free_ec(a)</code>
<code>end(f)</code>	<code>end_ec(f)</code>
<code>pos(f)</code>	<code>pos_ec(f)</code>
<code>f = opent(str)</code>	<code>f = opent_ec(str)</code>
<code>f = openb(str)</code>	<code>f = openb_ec(str)</code>
<code>seek(f, e)</code>	<code>x = seek_ec(f, e)</code>
<code>x = read(f)</code>	<code>x = read_ec(f)</code>

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