We present BIEBER (Byte-IdEntical Binary parsER), the first system to model and regenerate a full working parser from instrumented program executions. To achieve this, BIEBER exploits the regularity (e.g., header fields and array-like data structures) that is commonly found in file formats. Key generalization steps derive strided loops that parse input file data and rewrite concrete loop bounds with expressions over input file header bytes. These steps enable BIEBER to generalize parses of specific input files to obtain parsers that operate over input files of arbitrary size. BIEBER also incrementally and efficiently infers a decision tree that reads file header bytes to route input files of different types to inferred parsers of the appropriate type. The inferred parsers and decision tree are expressed in an intermediate language that is independent of the original program; separate backends (C and Perl in our prototype) can translate the intermediate representation into the same language as the original program (for a safer drop-in replacement), or automatically port to a different language. An empirical evaluation shows that BIEBER can successfully regenerate parsers for six file formats (waveform audio [1654 files], MT76x0 .BIN firmware containers [5 files], OS/2 1.x bitmap images [9 files], Windows 3.x bitmaps [9971 files], Windows 95/NT4 bitmaps [133 files], and Windows 98/2000 bitmaps [859 files]), correctly parsing 100% (≥ 99.98% when using standard held-out cross-validation) of the corresponding corpora. The regenerated parsers contain automatically inserted safety checks that eliminate common classes of errors such as memory errors. We find that BIEBER can help reverse-engineer file formats, because it automatically identifies predicates for the decision tree that relate to key semantics of the file format. We also discuss how BIEBER helped us detect and fix two new bugs in stb_image as well as independently rediscover and fix a known bug.
parser used to read the file, and BIEBER does not exploit or require any such information. BIEBER can therefore work with any existing parsers for our in-scope file formats (Section 2.1), provided they correctly parse the corpus of input files. Since each mapping is specific to the type and size of the file run through the instrumented parser, BIEBER processes log files from executions on multiple input files, and then integrates information from these multiple examples to obtain a regenerated parser decision tree that works on files of varying types and sizes. BIEBER implements several key techniques:

- **Loop Summarization**: BIEBER’s input is a flat listing of the data structure values as derived from the input file bytes, which is only accurate for files of the exact type and size as the file on which the instrumented application was run. To facilitate loop generalization, BIEBER first infers a loop (or set(s) of nested loops) that implement the specific translation for each input file. Key aspects of the algorithm include the ability to work with parsers that handle strided input or reorder input file bytes as they move into the data structures.

- **Loop Generalization**: BIEBER’s input does not contain information about loops, let alone how the loop bounds are derived. To produce parsers that generalize to input files of different sizes, BIEBER correlates values in the concrete loop bounds with values in the input file header, to infer bounds expressions that generalize these loops to files of different sizes.

- **Parsing Multiple File Types via a Decision Tree**: Input files often have different types, requiring distinct parsing strategies; for example, waveform audio may store samples with different bit-depths or number of channels. To create a combined parser that can works for all of the input file types, BIEBER generates a decision tree that incorporates inferred predicates on relevant input file bytes to route each file to a parser of the corresponding type.

- **Iterative Generalization**: To drive down the overhead associated with executing instrumented versions of the existing parser, BIEBER exploits file size and execution time properties. First, small input files require much less time to process than large input files. BIEBER therefore processes the files in the test corpus in order from smallest to largest. Second, BIEBER’s regenerated parser takes much less time to execute than the instrumented version of the existing parser. BIEBER therefore adopts an optimized technique that first executes the regenerated parser (without instrumentation) on the next file in turn. Only if the parse fails does BIEBER then execute the instrumented version (with associated overhead) of the existing parser.

  Our results show that our optimizations significantly reduce the number of instrumented executions. For example, to build the complete decision tree parser (consisting of 20 leaves/type-specific parsers) for the corpus of 11,008 bitmap files, BIEBER only executes the instrumented version of the application for 74 input files.

- **Improved Code through Regeneration**: BIEBER’s algorithms output an intermediate representation that can be translated to different languages by using an appropriate backend; the regenerated code need not be the same language as the original program. This allows convenient “porting” of the parser to different languages (C and Perl in BIEBER’s prototype). Moreover, if the target language is not inherently memory-safe, BIEBER enforces memory safety by passing all writes to the arrays that hold the parsed data through a helper function. This helper function performs all required bounds checks; resizable arrays support inputs of arbitrary sizes.

  BIEBER also helped identify inputs that triggered corner case bugs: one of our test applications, a bitmap parser, contained two previously unknown bugs that caused some (uncommon case)
bitmaps to parse (and therefore display) incorrectly.\footnote{We have reported these to the developers, and one has since been fixed.} The BIEBER-generated decision tree contained a distinct parser (or parsers, if the parsers for the buggy files failed to generalize) for each of the classes of inputs that trigger each bug — it routed all input files that trigger the bug, and only those files, to the corresponding parser. This isolation of the bug-triggering inputs helped us discover and correct these bugs. When we reran BIEBER on the corrected application, BIEBER generated a simplified decision tree that grouped these inputs together with other inputs that did not trigger the bugs. The decision tree automatically identified predicates that are meaningful to the file format semantics – without using the file specification – which we found useful for surfacing anomalies in the existing parser and enhancing our understanding of the file format.

### 1.1 Contributions

BIEBER is the first system to model and regenerate a full working parser from instrumented program executions. Because the regenerated parser produces data structures that are byte-for-byte identical to the data structures in the original program, the regenerated parser comprises an immediate drop-in replacement for the original parser. BIEBER does \textit{not} use control-flow information, and instead leverages a combination of inference techniques to automatically extract structured properties of the file format.

This paper presents:

- **Algorithms for Modeling and Regenerating Parsers:** We present the aforementioned techniques of loop summarization, loop generalization, parsing multiple file types via a decision tree, iterative generalization, and improved code through regeneration.

- **Empirical Evaluation:** We have implemented those algorithms in the BIEBER system. BIEBER generates working code — whereby the target language can be chosen independently of the language of the original code, simply by selecting a different backend — that includes systematically generated checks where necessary. We evaluate BIEBER on six file formats: waveform audio, MT76x0 .BIN firmware containers, OS/2 1.x bitmaps, Windows 3.x bitmaps, Windows 95/NT4 bitmaps, and Windows 98/2000 bitmaps. The results show that BIEBER efficiently models and regenerates parsers that successfully parse all input file types represented in the training set, generalizing to many files beyond those in the training set. Additionally, the decision trees built by BIEBER have automatically identified predicates that are important to the file formats. We also discuss how BIEBER assisted in uncovering two previously unreported bugs in \texttt{stb\_image}.

### 1.2 Structure of the Paper

Section 2 describes the binary data formats that are in scope for BIEBER, along with the expected format of the instrumentation logs. The subsequent four sections describe BIEBER’s key algorithms (Figure 1): Section 3 presents loop summarization algorithms, which infers structured for-loops from the flat instrumentation logs; Section 4 presents our algorithm to identify and rewrite key constants to more general expressions, generalizing our parsers along key dimensions; Section 5 introduces a recursive algorithm to build a parser decision tree that can correctly parse inputs of different types, with optimizations to reduce training time; and Section 6 discusses BIEBER’s C and Perl backends. Section 7 describes the methodology used to evaluate BIEBER’s ability to regenerate parsers, improve security, provide insight into how the parser processes a file format, and discover bugs; Section 8 presents the results. Section 9 describes related work, and Section 10 concludes.
Fig. 1. The BIEBER pipeline.

2 FILE FORMATS

2.1 In-scope File Formats

BIEBER infers binary data formats that may contain several features, individually or in combination. We now outline the challenges associated with each of these and the advantages of using BIEBER to tackle them.

Starting point: We assume we have only one “type”, with fixed-length input and output buffer, where each output byte is a deterministic function of one or more input bytes. For example, early versions of the ICO icon format (monochrome images with a fixed width/height of 16x16 pixels) meet this definition. For these cases, header bytes are not necessary for the parser to identify the “type” of the file (since we assume there is only one type) nor the length of any data (since the input and output are fixed-length). Nonetheless, file formats with these features suffice to demonstrate many of BIEBER’s capabilities and benefits: regenerating a compilable parser from execution logs (encoded using Z3 expressions: see Appendix A.2) requires significant processing by BIEBER; moreover, regeneration provides benefits, such as porting to a different language.

Enhancement A: Variable length “chunks”. File formats can be enriched by allowing variable-length data, with the length stored in the header. This is similar to the Resource Interchange File Format (RIFF) [rif 2018] “family” of file formats. Parsers for these formats are often vulnerable to a common class of bugs (buffer overflows), since the size of the output buffer may not be correctly computed. For example, CVE-2013-2028 is “chunked Transfer-Encoding request with a large chunk size” [chu 2013].

The instrumentation logs used by BIEBER do not contain information about the original looping structure in the parser. This looping structure is needed to generalize over varying sizes. BIEBER therefore introduces loop summarization (Section 3) and expression rewriting (Section 4) to infer this structure. Without those algorithms, a parser would conflate varying file sizes with varying file types, thus failing to generalize to unseen sizes and resulting in special-casing each unique size observed.

3“type” will be precisely defined in Section 5.1. For now, our intuitive understanding will suffice: for example, monochrome vs. 24-bit color images are different file types, but the width/height of the image does not affect the type.
**Enhancement B: Multiple file types.** File formats can support multiple types (for example, mono vs. stereo audio files), which have to be distinguished based on expressions over the header bytes. This complication is orthogonal to Enhancement A, as varying file formats could be present with fixed lengths. Notice that, even though in the simplest case each file type has a fixed length, buffer overflows are still possible, as the parser can misidentify the file type (resulting in an incorrect fixed length). Similarly to Enhancement A, given that the BIEBER instrumentation log files do not include control-flow information, BIEBER has to infer the relevant header bytes that indicate the file type. To tackle this challenge, BIEBER infers file-type separating predicates as part of its decision tree algorithm (Section 5).

**Composition of Enhancements.** Enhancements A and B are orthogonal: we can have multiple fixed-length types, or a single variable-length type. BIEBER can also handle file formats that contain both enhancements i.e., multiple variable-length types. This is significantly harder than solving either enhancement in isolation. If we only had Enhancement A (only one type of file, but with variable-length chunks), there is less ambiguity about the header bytes since, by definition of a single file type, all the inputs share the same header format. BIEBER’s algorithms (Section 4) handle the more complicated case of identifying header fields when there are multiple file types.

### 2.2 Out-of-scope File Formats
The features that we have selected are a subset of the features found in many common file formats, and are sufficient for BIEBER to regenerate parsers for several commonly used file formats (see Section 7). However, these features are not sufficient to parse all file formats that a user may be interested in. Nonetheless, we believe that the principles presented here are illustrative of the approaches required to extend BIEBER with additional features, which would allow regenerating parsers for a broader range of formats.

### 2.3 Instrumentation Log Format
The input to BIEBER’s pipeline is a mapping from input file bytes to output data structures that hold the parsed data. Our BIEBER prototype uses DIODE [Sidiroglou-Douskos et al. 2015], an off-the-shelf instrumentation tool for byte-level data-flow tracking. BIEBER does not depend on how the mapping is obtained, but as shorthand, we will refer to the mapping files as “DIODE logs”.

Given a concrete input file and an instrumented parser, DIODE emits symbolic expressions (in Z3 format [De Moura and Bjørner 2008]) for the output variables as a function of the input bytes. These symbolic expressions capture only the mapping generated by that particular execution and thus only describe the execution for inputs of the exact same type and size as the file parsed by the instrumented parser. The logs are, after some pre-processing, of the form \( \text{out}[i] = f(\text{in}[j_1], \ldots, \text{in}[j_n]) \), where \( \text{out} \) corresponds to a data structure, \( \text{in} \) corresponds to the input file pointer, \( i, j_1, \ldots, j_n \) are offsets such that \( x[i] \) refers to the byte at position \( i \) in \( x \), and \( f(\cdot) \) is some byte-level expression over its arguments. See Appendix A.2 for an example of a DIODE log file and Appendix A.1 for an example of a Z3 symbolic expression.

### 3 SUMMARIZE LOOPS
The input-output index mappings produced by DIODE describe the translation between input-output bytes for a single input type (for example, an audio file with a fixed number of channels and samples, or an image of fixed width, height, and bit-depth). We therefore need to generalize the mapping to work with inputs of variable length.

This step rewrites the input-output index mappings into a succinct form where BIEBER can, at a later stage, alter a key dimension: size. By summarizing the input-output index mappings into
a loop, we can subsequently induce parsing of new inputs by rewriting the loop bounds as an expression of header field bytes (Section 4).

**Basic summarization algorithm.** BIEBER performs linear interpolation using the first two output-input index pairs. For example, with index pairs of:

\[
\text{out}[0] = \text{in}[44]; \quad \text{out}[1] = \text{in}[46]; \quad \text{out}[2] = \text{in}[48]; \\
\ldots \quad \text{out}[9] = \text{in}[60];
\]

BIEBER interpolates the first two “points”, (0, 44) and (1, 46), to obtain:

\[\text{inputIndex} = (\text{outputIndex} \times 2) + 44\]

BIEBER then generates a for loop, with the upper-bound set to match as many output-input index pairs as possible (in this example, \(\text{outputIndex} \in [0..9]\)). For bottom-up bitmaps, one iteration of this process will capture only a single row of pixels; thus, BIEBER repeats this interpolation until all index pairs are part of a loop body (for example, one for loop per row of pixels, in the case of bottom-up bitmaps). BIEBER then applies the same process to the for loops’ bounds to create nested loops (e.g., a 2D loop for bottom-up bitmaps), until a fixed point is reached. Linear interpolation always matches at least the two points that the line was fit through, thus guaranteeing convergence.

**Finding the optimal stride.** The “stride” parameter controls how many bytes of input are processed in each iteration of an innermost for loop. Conceptually, BIEBER treats the input \(\text{in}[i]\) as different widths according to the stride; for example, if the stride is 3 bytes, then \(\text{in}[2]\) consists of bytes 6..8 of the input.

The basic summarization algorithm generates loops that accurately describe the concrete input/output index mapping, regardless of the chosen stride value. To determine an appropriate stride, we rely on a parsimony heuristic to choose the stride that results in the fewest bytes of generated intermediate representation. Our intuition is that the most compact representation is more likely to group together logically related output bytes.

### 3.1 Case Study 1: Waveform Audio Parser

Figure 2 shows an excerpt of the parser (left channel, least-significant byte) generated for a 16-bit stereo audio file. Note that BIEBER’s algorithms generate an intermediate representation that can be converted to different languages by selecting the appropriate backend (C or Perl in our prototype).

```plaintext
MIN_X := 7;
MIN_Y := 44;
MIN_Y0_0 := MIN_Y + 0;
LOOP_BOUND_A := 19840; // readWord_32le_s (fp, 40);
FACTOR_B_0 := 2;
for (idxA := 0; idxA < LOOP_BOUND_A; idxA += 4) {
    NUMERIC_A_0 := indexA * FACTOR_B_0;
    NUMERIC_A_1 := indexA;
    x0 := NUMERIC_A_0 + MIN_X;
    y0_0 := NUMERIC_A_1 + MIN_Y0_0;
    DATA_STRUCTURE [x0] := DIODE_EXPR (y0_0, file);
}
```

Fig. 2. Excerpt from a BIEBER generated parser for a 16-bit stereo audio file. The rewritten constant, shown in the comments, would generalize the parser to inputs of different length. We abstract out the repeated expression over input bytes as DIODE_EXPR.
3.2 Case Study 2: Bitmap Parser

Figure 3 shows the parser that is generated for a 61x76 24-bit (BGR) bottom-up bitmap. The summarization algorithm identifies how the input format (bottom-up, BGR, rows padded to a multiple of four bytes) is transformed to stb_image’s output format (top-down, RGB, no padding).

MIN_Y := 54; // readWord_32le_s (fp, 10);
MIN_Y0_0 := MIN_Y + 2;
MIN_X := 0;
LOOP_BOUND_A := 61; // readWord_32le_s (fp, 18);
LOOP_BOUND_B := 76; // readWord_32le_s (fp, 22);
FACTOR_B_0 := 3;
FACTOR_B_2 := 3;
FACTOR_C_0 := 183; // LOOP_BOUND_A * FACTOR_B_0;
FACTOR_C_1 := -184; // pad4(-LOOP_BOUND_A * FACTOR_B_0);
ADDITION_C_1 := -75; // (-LOOP_BOUND_B + 1);
for (idxB := 0; idxB < LOOP_BOUND_B; idxB ++) {
    NUM_B_1 := idxB * FACTOR_C_0;
    NUM_B_3 := (idxB + ADDITION_C_1) * FACTOR_C_1;
    for (idxA := 0; idxA < LOOP_BOUND_A; idxA ++) {
        NUM_A_0 := idxA * FACTOR_B_0 + NUM_B_1;
        NUM_A_1 := idxA * FACTOR_B_2 + NUM_B_3;
        x0 := NUM_A_0 + MIN_X; y0_0 := NUM_A_1 + MIN_Y0_0;
        DATA_STRUCTURE [x0] := DIODE_EXPR (y0_0, file)); // Blue subpixel
        x1 := x0 + 1; y1_0 := y0_0 + (-1);
        DATA_STRUCTURE [x1] := DIODE_EXPR (y1_0, file)); // Green subpixel
        x2 := x0 + 2; y2_0 := y0_0 + (-2);
        DATA_STRUCTURE [x2] := DIODE_EXPR (y2_0, file)); // Red subpixel
    }
}

Fig. 3. BIEBER’s generated parser for a 61x76 BGR bottom-up bitmap. The rewritten constants, shown in the comments, generalize the parser to inputs of different width, height and bitmap version. BIEBER abstracts out a repeated expression over input file bytes as DIODE_EXPR.

The stride of 3 bytes for the BGR parser is encoded as FACTOR_B_2 in Figure 3. Figure 4 shows that the optimal stride of 3 for BGR images was automatically detected by our parsimony heuristic. A stride of 1 byte also results in reasonably compact code for BGR images; this is because, to reverse the RGB ⇔ BGR subpixels, BIEBER can choose between:

out[i] = in[i+2]; out[i+1] = in[i+1]; out[i+2] = in[i];
or: for (j = 0; j < 3; j++) { out [i+j] = in [i+(2-j)]; }

For 32-bit bottom-up images, BIEBER correctly identifies that 4 bytes is the best stride (Figure 4).

4 IDENTIFY HEADER FIELDS AND EXPRESSIONS

Loop summarization created a set of for loops representing the output-input index mapping for each expression, with fixed loop bounds. A parser derived from this mapping will work only for inputs of the same size (e.g., audio length or image width/height) and type as the training example.

To generalize the parser to work across inputs of different size (but same type), we rewrite a subset of constant definitions as arithmetic expressions over key constants, and then replace key constants with reads over header fields. This rewriting process is applied to BIEBER’s intermediate representation, thus it is independent of the target language.
**Fig. 4. Stride detection.** Number of bytes of code generated for each stride, for 23x73 24- and 32-bit bottom-up bitmaps. Our parsimony heuristic can correctly identify the optimal strides of 3 and 4 bytes respectively.

### 4.1 Rewrite constants as expressions

BIEBER first identifies the set of constants that are candidates for rewriting in the generated parser IR (e.g., Figures 2 and 3). The code generated by the loop summarization stage was designed to facilitate this rewrite: for-loops are simplified to be zero-indexed with use of the < and a simple constant loop bound (which can represent key format properties — such as length for audio or width/height for bitmaps — which can be read from the input file), with traversal complexity shifted to the FACTOR, ADDEND and MIN_Y/MIN_Y0_0 variables. Only FACTOR and ADDEND are candidates for rewriting; MIN_X, MIN_Y and MIN_Y0_0 are simple offsets into the output and input data. BIEBER generates candidate expressions by instantiating a fixed set of templates with variables. These templates were designed to cover common file format properties, but can be easily extended:

- \(-x + 1\) // upside-down or reverse
- \(x \times y\), \(-x \times y\)
- \(\text{pad4 } (x \times y)\), \(\text{pad4 } (-x \times y)\) // word-aligned

When rewriting expressions in loops, it is often the case that inner nested loops depend on constants from outer loops e.g., \(\text{FACTOR}_C \_0 = \text{LOOP_BOUND}_A \times \text{FACTOR}_B \_0\); for example, with bottom-up bitmaps, the outer loop keeps track of the height, and code inside the inner loop uses both the width and height to calculate the offset of each subpixel. BIEBER therefore restricts the new expressions to use only variables that are in-scope (i.e., at an outer nesting level).

**Resolving ambiguity through voting.** In Figure 3, given:

\[
\text{LOOP_BOUND}_A = 61; \quad \text{LOOP_BOUND}_B = 76; \quad \text{FACTOR}_B \_0 = 3; \quad \text{FACTOR}_C \_0 = 183;
\]

\(\text{FACTOR}_C \_0\) is \(\text{LOOP_BOUND}_A \times \text{FACTOR}_B \_0\) is the only parsimonious rewrite produced by our templates. Often, however, constant definitions can be rewritten in many different ways, especially if the input dimensions are small or indistinguishable (e.g., for square bitmaps, the width field \(\text{LOOP_BOUND}_A\) and height field \(\text{LOOP_BOUND}_B\) are equal).

To handle competing rewrites, BIEBER employs a plurality-based voting scheme that integrates information from multiple exemplar files. For each input file, BIEBER computes the n-fold Cartesian product of candidate constant rewrites for each variable, and casts one vote per n-tuple. BIEBER then chooses the n-tuple with the most votes across all input files. If there are multiple equally popular n-tuples, BIEBER again opts for parsimony, and chooses the n-tuple with the shortest
aggregate string representation (e.g., if \texttt{pad4(x)} and \texttt{x} are equally popular, BIEBER chooses \texttt{x}). Any further ties are broken arbitrarily. The parser created using this \textit{n}-tuple will, by construction, work for at least one input file. The \textit{n}-fold Cartesian product used in this voting scheme has, in the worst-case, exponential time and memory complexity. However, it is tractable in practice because of the small number of variables involved, in part because BIEBER’s loop summarization step minimizes the number of loops. We discuss polynomial-time algorithms in Appendix A.5.

An advantage of our voting scheme is that a single disambiguating example often suffices to induce a correctly generalized parser. For example, if BIEBER trained on 10 square images and 1 non-square image, our algorithm would regenerate a parser that works on rectangular images. Indeed, in practice we have observed that our voting scheme resolves the ambiguity in most cases.

**Robustness.** A key insight is that, due to the downstream parser decision tree (Section 5), BIEBER does not need rewrites to be correct for all, or even many of the inputs: it only needs it to work for at least one of the inputs given any arbitrary set of inputs (including recursively on the remaining inputs)

### 4.2 Replace remaining constants with header bytes

The second step in this rewrite phase is to identify the remaining constants that can be replaced with header bytes e.g., \texttt{LOOP\_BOUND\_A/B} and \texttt{MIN\_Y} in Figure 3. The header contains metadata, such as the sizes of payloads in MT76x0 firmware containers, or the width and height of a bitmap.

**Header section identification.** The header is defined as the section from the beginning of the file, up to the start of the first data chunk. Some file formats (e.g., MT76x0 containers) contain a fixed-size header, followed by the data chunks. Other formats (e.g., BMP) store the header size (or, equivalently, offset of the data chunk) as a field inside the header itself; this can be viewed as a small, fixed-size header that contains the size of additional header sections, thus reducing the problem to that of fixed-size headers.

Since BIEBER is not given the file specification, BIEBER must infer the header size. If BIEBER overestimates the header size, the search procedure will take longer, and there may be many false positives of header bytes that coincidentally match constants in the generated IR. Conversely, if BIEBER underestimates the header size, BIEBER may fail to replace some constants with header bytes. In both cases, BIEBER will still be able to parse 100\% of the training set (see “Robustness” subsection below), though the regenerated code may not fully generalize. BIEBER therefore starts with a small header size estimate (32 bytes), and increases it until BIEBER can generate a generalized parser.

**Rewriting process.** BIEBER first filters out any input files that are not consistent with the rewrites from the previous step (i.e., files that contradict the \textit{n}-tuple chosen during voting). Next, for each \texttt{LOOP\_BOUND} and \texttt{MIN\_Y} variable, BIEBER packs the concrete value into different types: 8-bit, 16-bit, 32-bit, and 64-bit integers (little endian), with both unsigned and signed variants (e.g., the bitmap height is negative to denote top-down bitmaps). BIEBER compares the packed value against the header to find possible matching locations. BIEBER also considers whether a concrete value can be rewritten as the product (or negated product) of two header fields

\footnote{We do prefer to create a parser that accepts as many inputs as possible.}

\footnote{The previous step, “Rewriting constants as expressions” (Section 4.1) cannot rewrite the loop bound of top-down unpadded bitmaps as a product of the width and height (and stride), because the width and height do not appear as other constants, and there are generally many different combinations of width/height that result in the same input/output index mapping. For example, 1x4, 2x2, and 4x1 top-down BGRA bitmaps all share the same mapping, hence it is impossible to infer the width/height from the mapping alone, without comparing against the header bytes.

\footnote{In the general case, the formula needs to take into account strides, nested loops, and bottom-up mappings.}}
For each variable, if there is no matching location, BIEBER assumes that it is a bona fide constant, and does not replace it. For example, MT76x0 firmware images have a fixed header size of 32 bytes, and therefore the first data chunk begins at byte 32; 32 bytes is a property of the file format, and does not appear as a field in the input file. Similarly, when stb_image reads in a 16-bit bitmap, it outputs a 24-bit image; 24-bit is a property of stb_image, and does not appear in the input file.

**Ambiguity.** BIEBER cannot distinguish between signed vs. unsigned if the input files do not have any values large enough to only fit in unsigned integers, nor between different widths (e.g., int16 vs. int32) if there are coincidental zero values next to the variable (for example, AD DE 00 00 could be a 16-bit little-endian field [with value 0xDEAD] and 16-bits of zeros to the right — that may be padding or belong to another variable — or a 32-bit little-endian field [with value 0xDEAD]). Additionally, BIEBER cannot accurately identify the dimension header fields (e.g., width and height for bitmap images) if the training data is ambiguous (e.g., square bitmaps).

**Robustness.** As per rewriting constant definitions (Section 4.1), BIEBER’s downstream parser decision tree means that this step only needs to replace constants in a manner that works for at least one of the input files. BIEBER employs a similar n-fold Cartesian product voting scheme in this step. Ties are broken by choosing the widest type possible. This allows generalization to larger files, even when trained on small files. If BIEBER had erroneously chosen a wider type, it would discover this relatively quickly, because any counterexample input must be small. For example, suppose that the training data does not disambiguate whether the length field is 8-bit, 16-bit or 32-bit. If BIEBER chooses the widest type (32-bit), but the ground truth is that the length field is 8-bit, then there exists a counter-example input with a $\leq 255$-byte data chunk.

5 **MERGE PARSERS INTO DECISION TREE**

In the worst case, the algorithms so far are guaranteed to generate a parser — albeit possibly with concrete loop bounds — that can parse at least one of the inputs from the training set. In this section, we explain how, using only this worst-case guarantee, BIEBER can build a parser decision tree that converges to parsing all types represented in the training data.

5.1 **Parse by Type**

**Definition 5.1.** A file’s signature corresponds to a subset of bytes in the header that determine the execution path through the original parsing program. We say two files share the same signature, if they have the same values at the corresponding header positions.

We consider any files with the same signature to be of the same type. Files of the same type should be accepted by the same parser, assuming the proper loop bound generalization and excluding files with non-header-dependent data transformations. The intuition is that we can model individual parsers, which generalize to properties such as width and height (for bitmaps) or number of samples (for audio), for each type of input (e.g., 16- vs. 24-bit bitmaps, 8- or 16-bit audio), and then assemble these parsers into a decision tree that dispatches a new input to the correct parser based on certain values in the input’s header (e.g., the file signature).

We define a language (Figure 5) for constructing the parser decision tree as a collection of individual parsers guarded by predicates over file signatures. Nodes in this tree correspond to a predicate, with a branch for input files that satisfy the predicate and a branch for those that do not. A leaf in the tree corresponds to a parser we have regenerated. Parsing a file corresponds to traversing this tree until a leaf is reached. The parser decision tree is generated as BIEBER IR, and an appropriate backend handles code generation (Section 6).
Fig. 5. Tree-based parser DSL. \textit{Parsers} corresponds to the set of type-specific individual parsers regenerated so far in the BIEBER pipeline, each of which can parse a type of input, and \textit{pred} is the set of boolean predicates over inputs’ signatures.

5.2 Building a decision tree, given a fixed set of DIODE logs

We begin with the simple case where we have a fixed set of DIODE logs, corresponding to a subset of input files. Algorithm 1 presents the core algorithm to model and regenerate a tree-based parser. Given a newly generated parser, each input file can be annotated as correctly or incorrectly parsed by comparing the output of the generated parser against the reference application (which plays the role of a functionality oracle). If all examples have been correctly parsed, then we create a leaf that contains that parsing program, \textit{indivParser}.

Section 4’s robustness guarantee is that for any set of input files and their corresponding DIODE logs, the generated \textit{indivParser} will parse at least one of the input files. Thus, the only circumstance in which \textit{indivParser} cannot parse any input files is if we do not have any DIODE logs. In this case, we create a leaf with a null parser, where no files will be parsed. This will be resolved when we expand our set of DIODE logs (discussed below). If we have DIODE logs for all input files, we are guaranteed to produce a tree with leaves where all inputs can be parsed, since we can trivially add a file’s full signature (one byte at a time) as the required predicate nodes in the tree.

If \textit{indivParser} works on only some of the inputs (i.e., it fails to parse a proper subset of the input files), we would ideally split the inputs based on which ones are parseable, and then call the tree-building algorithm recursively on only the unparseable inputs. We approximate this behavior using the \texttt{pickAHew} function (Algorithm 2) which finds an equality predicate on a file signature byte that maximally distinguishes the parseable vs. unparseable bitmaps.

5.3 Choosing a small set of logs

Applying Algorithm 1 to a complete set of DIODE logs would create a decision tree that parses the entire training set. However, generating the necessary logs can be computationally expensive, and wasteful, as BIEBER can generalize from a few representatives of each input type. Small inputs and large inputs of the same type create identical parsers (when appropriately generalized), despite their different overheads; thus, our goal is to generate logs only by executing the instrumented application with the smaller input files.\footnote{Sometimes DIODE logs from smaller inputs may have more ambiguity when rewriting or replacing constants. If this results in a parser that is not sufficiently general, Algorithm 3 will correct this in a later iteration by generating logs for the larger, unparseable input.}

Algorithm 3 shows our iterative process to select the smallest unparseable input files, create DIODE logs for these and build the parser tree. The process repeats until the parser tree has sufficiently high coverage of available inputs. We can inexpensively test whether an input is parseable by our current parser tree, by comparing its output with that of the original application.

Our BIEBER prototype generates logs for 10 unparseable files at a time to exploit CPU parallelism.\footnote{10 files is based on our workstation properties.}

If, at each iteration, we obtained the log for only the smallest unparseable file, we would end up with the minimal set of logs.

\begin{verbatim}
\texttt{tree} := \texttt{Leaf}(\texttt{indivParser} \in \texttt{Parsers}|\texttt{null}) \\
| \texttt{Node}(p \in \texttt{pred}, b_{\texttt{true}} \in \texttt{tree}, b_{\texttt{false}} \in \texttt{tree})
\end{verbatim}

\begin{verbatim}
\texttt{pred} := \texttt{byte}_i = c \in \mathbb{Z}
\end{verbatim}
Algorithm 1 Inferring a tree-based parser

**Input:** example input files examples, DIODE log files logs, the original application oracle  
**Output:** A tree that can be compiled into the complete parser

```plaintext
function BuildTree(examples, logs, oracle)
    indivParser ← BuildIndivParser(examples, logs)
    (parseable, unparseable) ← TestParser(parseTree, corpus, oracle)
    if |unparseable| == 0 then
        return Leaf(indivParser)
    else if |parseable| == 0 then
        return Leaf(null)
    else
        predicate ← PickAHew(parseable, unparseable)
        (sat, unsat) ← Split examples on predicate
        if (|sat| == 0) ∨ (|unsat| == 0) then
            return Error("Cannot find predicate in header. Try increasing header size.")
        else
            left ← BuildTree(sat, logs, oracle)
            right ← BuildTree(unsat, logs, oracle)
            return Node(predicate, left, right)
        end if
    end if
end function
```

Algorithm 2 Finding an equality predicate, to create a split node in the decision tree, that hews good vs. bad files

**Input:** goodFiles, which are successfully parsed, and badFiles, which fail to be parsed  
**Output:** An equality predicate over byte index \( i \) and value \( v \), to hew files.

```plaintext
function PickAHew(goodFiles, badFiles)
    for all \( i \in [0..\text{headerSize}) \) do
        for all file ∈ goodFiles do
            freq[i][file[i]] += 1
        end for
        for all file ∈ badFiles do
            freq[i][file[i]] -= 1
        end for
    end for
    \( \hat{i}, \hat{v} \) ← argmax_{i,v}(|freq[i][v]| - \( i \)) \>
    
return \( \lambda f : file.f[\hat{i}] == \hat{v} \) \>
end function
```

6 EMIT HARDENED CODE

BIEBER’s use of an intermediate representation means that, by choosing a different backend, BIEBER can regenerate parsers in multiple languages: the same language as the original, for a drop-in replacement; or a different language, for automatic porting. BIEBER’s prototype has two backends (C and Perl), which illustrate these two use cases, as well as vastly different points in the design space: C is a compiled language (Perl is interpreted); C lacks memory safety (BIEBER’s...
Algorithm 3 Choosing a small set of logs

Input: application app, input files corpus, DIODE logs logs
Output: A tree that can be compiled into the full parser, and a small set of DIODE logs

function EXPANDLOGSUNTILCONVERGED(corpus, oracle)

logs ← nil, parserTree ← null, parseable ← nil, unparseable ← corpus

while (|unparseable| ≥ 0) do
    fails ← GETSMALLEST(10, unparseable)  // coverage guarantee
    logs ← logs + GETDIODELOGS(fails)
    parserTree ← BUILDTREE(corpus, logs, oracle);
    (parseable, unparseable) ← TESTPARSER(parserTree, corpus, oracle)
end while
return parserTree, logs
end function

wrapper functions add spatial memory safety in the regenerated parsers; Perl natively provides memory safety); and, critically, C directly exposes machine data types (e.g., uint64_t; Perl does not).

6.1 Backend #1: Lowering Z3 to C

Z3 code supports arbitrary-width bit-vectors [Microsoft Research [n.d.]]. In the general case of converting Z3 to C, BIEBER would need to implement bit-vector support as well. However, the key insight is that DIODE’s Z3 bit-vectors are used solely to represent/“lift” LLVM IR, and hence are exactly 8/16/32/64/128-bit. BIEBER is therefore able to optimize the translation by mapping/“lowering” these bit-vectors back to C’s fixed-width data types (e.g., (_ BitVec n) maps to int64_t/uint64_t); moreover, operations on Z3 bit-vectors map cleanly to operations using C’s data types (e.g., Z3’s explicit zero-extend and sign-extend operators are equivalent to C code that assigns to a larger-width unsigned and signed int respectively; see Table 6).

| Operation              | Z3                                      | C                           |
|------------------------|-----------------------------------------|------------------------------|
| Sign extend            | (_ sign_extend 32) x                    | int64_t y = (int32_t) x;     |
| Zero extend            | (_ zero_extend 32) x                    | int64_t y = (uint32_t) x;    |
| Extract bits           | (_ extract 31 16) x                     | int16_t y = x » 16;          |
| Arithmetic shift-right | bvashr x bv16                           | int32_t y = (bit32_t) x » 16;|
| Logical shift-right    | bvlshr x bv16                           | int32_t y = ((bit32_t) x) » 16; // sign-extend |
| Shift-left             | bvhsl x bv16                            | int32_t y = x » 16; // arithmetic shift = logical shift |

Fig. 6. Examples of lowering DIODE’s Z3 expressions to C. Assume that x is a 32-bit bit-vector in Z3, declared as int32_t x; in C.

6.2 Backend #2: Emulating Z3 in Perl

Figure 6 showed that C’s fixed-width data types were essential for efficiently lowering Z3. Unfortunately, Perl does not directly expose machine data types; the interpreter can choose to store numbers as native integers, native floating-point, or decimal strings, converting between them as

9We could import the Z3 C bindings instead, but this adds a heavyweight dependency to the regenerated parser.

10Z3 does not have “signed” vs “unsigned” bitvectors; rather, it is necessary to choose the appropriate arithmetic operator. [Microsoft Research [n.d.]]
necessary [Perl 5 Porters [n.d.]a]. The importance of explicit variable widths can be seen through a simple example. Suppose \( x = -1 \), and \( x \) is then zero-extended to a 16-bit bit-vector; it can be either: 
-1 (bit-vector: 1111111111111111) if \( x \) was originally 16-bit, or 255 (bit-vector: 0000000111111111) if \( x \) was originally 8-bit. Additionally, Perl does not expose all the primitives needed to efficiently map Z3’s operators; for example, all bit-shifts are logical shifts by default, unless the “use integer” pragma is enabled, in which case all bit-shifts become arithmetic shifts [Perl 5 Porters [n.d.]b].

BIEBER works around these limitations by “emulating”, instead of lowering, Z3. For example, Z3’s \texttt{bvmul} operator is mapped to a helper function \texttt{SLIMESupport::bvmul}, which internally uses the library function \texttt{Bit::Vector::Multiply}. The extra indirection of the \texttt{SLIMESupport} wrappers (instead of directly emitting \texttt{Bit::Vector::Multiply}) makes the code cleaner, and allows substituting the \texttt{SLIMESupport} library with a more efficient implementation in the future.

### 7 EVALUATION METHODOLOGY

We implemented BIEBER and used it to empirically evaluate the effectiveness of BIEBER’s algorithms. We describe the evaluation methodology in this section, and present the results in Section 8.

#### 7.1 Input Formats and Reference Parsers

We evaluate BIEBER using the WAV (waveform audio), OS/2 1.x bitmap, Windows 3.x bitmap, Windows 95/NT4 bitmap, and Windows 98/2000 bitmap, and MT76x0 firmware container formats. WAV and the BMP family are classic, eponymous file formats for waveform audio and bitmap images files, respectively [wav 2012; bmp 2018a,b]. Note that, as early as 1994 (i.e., predating the Windows 95/NT4 and 98/2000 bitmap formats), the BMP family was already recognized as “not a standard file format ... the BMP format is actually a sheaf of formats bundled under the same name” [bmp 1994]. MT76x0 firmware containers are used to store part of the firmware updates for wireless routers that use the MediaTek MT76x0 chipset.

BIEBER’s algorithms do not depend on how the mapping between input file bytes to data structure contents is obtained. For our prototype, we obtained these mappings by sending input files through three reference parsers, each of which has been instrumented with DIODE (with some minor changes to work around limitations of the DIODE prototype): SndLib, stb_image, and OpenWrt [2021]11. Table 1 summarizes the file formats and reference parsers used in our evaluation.

| File Extension | File formats                      | # files in corpus | Reference Parser |
|----------------|----------------------------------|-------------------|-----------------|
| WAV            | RIFF (little-endian) data, WAVE audio | 1,651             | SndLib          |
| BIN            | MT76x0 firmware containers | 5                 | OpenWrt         |
| BMP            | OS/2.1x format                  | 9                 | stb_image       |
|                | Windows 3.x format              | 9,971             |                 |
|                | Windows 95/NT4 and newer format | 133               |                 |
|                | Windows 98/2000 and newer format| 895               |                 |
| Combined corpus (input to BIEBER) | 11,008             |                   |                 |

Table 1. File formats in our evaluation.

11https://github.com/openwrt/mt76/blob/master/mt76x0/usb_mcu.c, with additional modifications to store the firmware container contents into a data structure rather than flashing the hardware device.
7.2 Corpora

WAV. We used a compilation of “999 WAVs for Windows”\textsuperscript{12}, which, name notwithstanding, contains 1585 WAV files. We excluded YMMUD.WAV, which is actually a plain-text file designed “to allow for the random selection of configured wav files to be played”. To increase file diversity, we also included all 70 .wav audio files from the C:\Windows\Media folder of a Windows 10 system. BIEBER is not given the provenance of the WAV files; its input is the combined corpus of 1654 WAV files.

These files differ based on the number of channels (mono vs. stereo), sampling rate, and recording length. The mapping from input file to in-memory data structures can be non-trivial; for stereo audio files, the input is interleaved channels, each containing 16-bit shorts, while the output is separate (left- and right-channel) arrays of 64-bit longs. Additionally, three WAV files\textsuperscript{13} contain extra metadata sections (instead of the canonical format-plus-data layout [Sapp nd]); we did not remove these files from the corpus, and BIEBER is able to parse them.

MT76x0 .BIN firmware containers. We downloaded all 621 driver tarballs (.tar.gz) from Fars Robotics Website [nd]. These tarballs contained 1106 .BIN files, which represented 2 unique variants\textsuperscript{14}; the tarballs contain changes to other files (e.g., .ko Linux kernel drivers), which are not in scope for this file format. Additionally, the Open Wireless Router [OpenWrt 2021] project’s sample firmware directory contains a further three unique variants\textsuperscript{15}, for a total corpus size of five firmware containers.

BMP. BIEBER can regenerate parsers for each of the four bitmap file formats (OS/2.1x, Windows 3.x, Windows 95/NT4, Windows 98/2000), each of which contains various subtypes (e.g., bottom-up vs. top-down; 16-bit vs. 24-bit, etc.). We will show a strictly stronger result: BIEBER can regenerate a parser decision tree that parses the combined corpus of all these file types. Files range in size from 6,966 bytes (48x48 24-bit) to 36,578,358 bytes (3024x4023 24-bit), with a total corpus size of 16,283,146,489 bytes (11,008 files).

We built the corpus by obtaining the top 10 most popular search phrases for each of the 25 English-text categories from Google’s Year in Search 2018 [goo 2018]. We then used google_images_download [Vasa 2019] to scrape the top 100 bitmap images from Google Image Search for each of the 232 unique keywords. This returned a median of 68 bitmaps per phrase (min 1, max 92) due to various errors (e.g., “Wrong image format returned”), for a total of 13,694 bitmaps. We filtered out: four files that are not “PC bitmap” (which were erroneously included by google_images_download), duplicate (byte-for-byte identical) copies of bitmaps (1980 files)\textsuperscript{16}, palettized bitmaps (448 files), and corrupted bitmaps (168 files which contains less pixel data than implied by the dimensions, and 86 32-bit bitmaps with all-zero alpha channels).

7.3 Training/test performance of entire parser tree

BIEBER regenerates the parser in the form of a decision tree, with individual parsers at the leaves. The first way to evaluate BIEBER’s performance is to consider the overall correctness of the regenerated parser. Algorithm 3 guarantees 100% correctness on the training set. To evaluate the generalizability of our automatically generated WAV and BMP parsers, we performed standard held-out cross-validation [James et al. 2013]. For each of the WAV and BMP corpora, we randomly split 80% into a training set (1353 WAVs or 8806 BMPs), ran the complete BIEBER pipeline, and then tested on the remaining held-out 20%. We repeated this process a total of 100 times to account for the random split. For MT76x0 firmware containers, due to the smaller corpus size, we used a

\textsuperscript{12}https://archive.org/details/cdrom-999wavsfowindows
\textsuperscript{13}BIG.WAV, BUTTHEAD.WAV, and CAFE80S.WAV
\textsuperscript{14}mt7610u.bin, mt7650u.bin
\textsuperscript{15}mt7610e.bin, mt7662.bin, mt7662_firmware_e3_v1.7.bin
\textsuperscript{16}BIEBER can successfully handle duplicates, but it inflates the correctness rate.
single firmware container as training input, and checked that BIEBER’s generated parser could parse the other firmware containers.

7.4 **Automatically identified predicates at nodes of parser decision tree**

The parser decision tree, as a whole, is useful for parsing the entire corpus. However, it is also notable that, for each of the nodes, Algorithm 2 can automatically choose predicates that are meaningful for the file format, **without** using the file specifications, nor any explicit control-flow information from the original parser (recall that the DIODE logs do not contain such information). We applied the BIEBER pipeline to the complete WAV and BMP corpora to create decision trees that can parse all the input files, and discuss some of the predicates that BIEBER has chosen. The MT76x0 firmware containers could all be parsed with a single leaf parser, hence there were no predicates identified nor needed.

7.5 **Optimized processing**

We estimate the runtime speedup of BIEBER’s ExpandLogsUntilConverged (Algorithm 3) compared to other file selection strategies.

7.6 **Bugs prevented or found**

We discuss how BIEBER’s regeneration process automatically prevents memory-safety bugs. Additionally, we will discuss two new bugs in the stb_image library that we found and reported\(^\text{17}\), and also a known bug that we independently rediscovered. Neither of the new bugs lead to memory-safety issues, and hence would not have been avoided by (re-)writing stb_image in a memory-safe language or running stb_image with a memory error detector such as AddressSanitizer [Serebryany et al. 2012]. We also conceptualize the general classes of bugs that BIEBER can help detect.

8 **RESULTS**

8.1 **Training/test performance of entire parser tree**

**WAV parser.** BIEBER’s decision trees correctly parsed between 99.76% and 100.00% of the entire WAV corpus (mean: 99.98%). The parsing failures occur when rare WAV classes are represented in the test set but not the training set.

**BMP parser.** BIEBER’s decision trees correctly parsed between 99.93% and 100.00% of the entire bitmap corpus (mean: 99.98% — coincidentally the same as the WAV parser). The parsing failures occur when rare BMP classes are represented in the test set but not the training set. For comparison, the original parser correctly parses only \( \approx 98\% \) of the corpus, because it contains bugs which BIEBER helped us find and fix (Section 8.4), and which our regenerated parser avoids.

**MT76x0 firmware container parser.** Training on any single file from the corpus sufficed to create a generalized parser for all inputs.

**Porting to other languages.** BIEBER’s backends are able to regenerate working C or Perl code that implement the decision trees (including the leaf parsers). Regenerating code in another language can be achieved by adding a different backend; BIEBER reuses the results from earlier steps (loop summarization, rewriting expressions, decision tree) in BIEBER’s pipeline, as those are performed exclusively on the intermediate representation. This means that BIEBER can produce high-correctness parsers for other languages, for which the alternative may otherwise be no parser available.

\(^\text{17}\)https://github.com/nothings/stb/issues/773, https://github.com/nothings/stb/issues/783
8.2 Automatically identified predicates at nodes of parser decision tree

**WAV parser.** The generated WAV parser decision tree (Figure 7) is a complete binary tree with 4 leaves (each leaf corresponds to a parser for a specific input file format) that correctly parses all 1651 WAV files in the corpus (i.e., 100% correctness). At each node, we show the predicate from its parent. For example, the root is split based on whether byte 32 of the file — the “block alignment” of the audio (i.e., number of channels * bytes per sample) — is 1, which corresponds to 8-bit mono audio; meanwhile, the predicate `in[22] == 2` checks the number of audio channels (i.e., if it is stereo). The predicates are all automatically selected by BIEBER (Algorithm 2), without using the WAV file specification. The leaves describe each parser’s functionality; for example, the left-most leaf corresponds to a parser for 8-bit mono audio files that lack extra metadata.

**BMP parser.** The generated BMP parser decision tree (Figure 8) is a complete binary tree with 20 leaves that correctly parses all 11,008 bitmaps (i.e., 100% correctness). BIEBER’s Algorithm 2 once again automatically selects relevant predicates, without using the file specification. For example, the root is split based on whether byte 28 of the file — the bit-depth of the image — is 24. The predicate `in[10] == 138` checks the offset of the pixel data in the file, or equivalently, the size of the header and therefore the “version” of the bitmap file format. Another internal node identifies whether an image is top-down (`height < 0`) or bottom-up (`height > 0`). Although our predicate selection (Algorithm 2) is designed to test strict equality of individual bytes, it is able to determine if the height field is negative by taking advantage of the two’s complement representation of 32-bit integers (`in[24] == 0`). Additionally, while our predicate selection algorithm is designed to test single bytes,
it chooses the correct parser for different 4-byte bitmasks by recursively partitioning on individual bytes until they are disambiguated, in a similar fashion to Blind ROP’s byte-by-byte discovery of stack canaries [Bittau et al. 2014]. Unlike Blind ROP’s hardcoded strategy, this byte-by-byte discovery is an emergent property of BIEBER’s decision tree algorithm.

8.3 Optimized processing

Table 2 shows the number of unparseable WAVs or BMPs (across all leaves of their parser decision tree) at the start of each round when using ExpandLogsUntilConverged (Algorithm 3).

The WAV parser results required two iterations of ExpandLogsUntilConverged, with DIODE logs for only 20 of the 1,654 WAVs. At the start of round 0, the entire corpus (1,654 WAVs, totaling 121MB) cannot be parsed. The smallest 10 WAVs total just 12KB; after obtaining DIODE logs for these smallest WAVs, only 73 WAVs (5% of the corpus by file count; 16.5% by file size) are unparseable. We then repeat the process by selecting the 10 next smallest unparseable WAVs (37KB), which suffices to reach convergence. In total, BIEBER required DIODE logs for just 0.4MB of WAVs (0.32% of the corpus by file size). The BMP parser results required eight iterations of ExpandLogsUntilConverged, with DIODE logs for only 74 of the 11,008 BMPs. In total, BIEBER obtained DIODE logs for just 12.8MB of BMPs (0.08% of the corpus by file size).

Comparison with other file selection strategies. We estimate that BIEBER’s optimized processing is orders of magnitude faster than other strategies. Since processing using those other strategies can take hundreds, or even thousands of CPU days to complete, it is impractical to directly measure their runtime. Instead, we estimate their runtime by measuring the amount of time required to generate DIODE logs for a subset of WAV and BMP files, then using these measurements to build performance models that characterize the time required to obtain the final BIEBER parser. With these models, the time to process a WAV file is \(0.2157B\) seconds, and the time required to process a BMP file is \(0.0692B\) seconds, where \(B\) is the number of bytes in the WAV or BMP file (e.g., a 10,000 byte BMP file takes approximately 692 seconds to process). Table 3 uses these models to compare the number of bytes of input needed to be run through the instrumented parser, and corresponding approximate CPU days required, for various file selection strategies.

In the absence of Algorithm 3 — which used the insight that we can test whether inputs are already parseable by our regenerated parsers — we would need to generate DIODE logs for all the files and feed them into Algorithm 1. For the bitmap corpus, this would be prohibitively expensive: roughly 13,000 CPU days. This is orders of magnitude slower than Algorithm 3, which only requires around 10 CPU days. We do have some extra overhead from rebuilding the tree and testing the parsers, but this is negligible compared to DIODE’s runtime.

We also model the runtime of Algorithm 3 with a different heuristic than choosing the smallest unparseable files at each round. When choosing the largest unparseable files, the modeled runtime is 500 CPU days; this is still much faster than running DIODE on all the logs, but also significantly slower than choosing the smallest files. We also tried random selection: the modeled runtimes were in between (roughly 70-80 days).

The results for the WAV corpus follow the same general pattern as the BMP corpus, again showing that Algorithm 3 with our smallest size heuristic provides a significant speedup (1 CPU day instead of up to 300 CPU days).

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18There are corner cases where it is not optimal. For example, suppose that the corpus consists of 10 small files of the same type, plus a large file of a different type: processing the 10 smallest files first would be less efficient than processing the 10 largest files.
Fig. 8. **Generated parser decision tree for stb_image’s BMP functionality.** The first line of each node denotes the decision tree predicate from its parent; the second line relates that inferred predicate to a key file format property. The last line of each leaf explains the file formats that can be parsed.
### Unparseable WAVs and BMPs

| Round | # files | # bytes (all) | # files (10 smallest) | # bytes (all) | # bytes (10 smallest) |
|-------|---------|---------------|------------------------|---------------|------------------------|
| 0     | 1654    | 121,464,191   | 11,747                 | 11,008        | 16,283,146,489         | 131,492                                      |
| 1     | 73      | 19,966,796    | 376,862                | 1,809         | 2,913,068,807          | 328,480                                      |
| 2     | 0       | 0             | 0                      | 1,260         | 2,059,278,713          | 591,480                                      |
| 3     |         |               | 1,085                  | 1,913,469,901 | 871,512                |
| 4     |         |               | 308                    | 736,009,768   | 1,247,716              |
| 5     |         |               | 106                    | 284,912,770   | 1,733,040              |
| 6     |         |               | 58                     | 191,820,812   | 3,890,752              |
| 7     | 1,085   | 1,913,469,901 |                        |               |                        |
| 8     |         |               | 4                      | 3,992,704     | 3,992,704              |

**TOTAL**: 388,609 bytes, 12,787,176 bytes

Table 2. **Number of unparseable BMP or WAV files (across all leaves) at different algorithm iterations.** Round 0 is the initial corpus of 1654 WAVs or 11,008 BMPs. At each round, BIEBER obtains DIODE logs for the 10 smallest unparseable bitmaps, and then re-runs BuildTree (Algorithm 1).

| Strategy         | BMP Input Bytes | WAV Input Bytes | BMP Est. CPU Days | WAV Est. CPU Days |
|------------------|-----------------|-----------------|-------------------|-------------------|
| Process all files| 16,283,146,489  | 121,464,191     | 13,041.6          | 303.2             |
| Smallest size first | 9,388,502   | 388,609         | 7.5               | 0.97              |
| Largest size first | 621,022,028 | 10,399,639      | 497.4             | 26.0              |
| Random (seed 1)  | 82,031,734     | 2,594,851       | 65.7              | 6.5               |
| Random (seed 2)  | 78,058,706     | 3,385,886       | 62.5              | 8.5               |
| Random (seed 3)  | 69,596,708     | 4,934,947       | 55.7              | 12.3              |

**TOTAL**

Table 3. **Estimated CPU days for different file selection strategies, based on our performance model.**

### 8.4 Bugs prevented or found

#### Memory safety enhancements

Our IR examples (DATA_STRUCTURE [x] = ... ) are evocative of direct array accesses. BIEBER’s C backend generates code that uses a wrapper function to prevent reading past the input bounds (Appendix A.3), and replaces the output array with a dynamic array to prevent any buffer over/under-flows (Appendix A.4). These enhancements are enabled in the backend, without needing developer input, changes to the original parser, or identification of any such bugs. BIEBER’s Perl backend omits these checks, since Perl internally enforces them.

**New bug #1 (not memory-safety related): missing bytes.** For 16-bit bitmaps with compression type 3 (user-specified red/green/blue bitmasks), stb_image skipped the first 12 bytes of the pixel data, because it did not account for the bitmasks when seeking from the end of the header to the start of the pixel data. We were able to identify this bug — *without* comparing stb_image to a second parser — because the DIODE logs for these bitmaps were also missing the first 12 bytes, which made loop abstraction impossible. The stb_image maintainer noted the bug report and fixed it in a subsequent release.

**New bug #2 (not memory-safety related): irrelevant bitmask.** For 32-bit bitmaps with compression type 0 (no bitmasks), the user-specified color channel bitmasks should be ignored according to the specification [bmp 2018a,b]. stb_image correctly checks the compression field for Windows 20
3.x bitmaps, but for Windows 95/98/2000 bitmaps, it always uses the bitmasks. For the vast majority of Windows 95/98/2000 32-bit bitmaps, this does not result in a bug, because the color channel bitmasks contain values equivalent to the default (BGRA). However, for ≈ 1% of our corpus, this has a visible discrepancy, because the bitmask specifies RGBA. Our tree partitioning algorithm grouped these images into their own “RGBA-parser” leaf, making it easy to identify this class of bug-triggering inputs by inspection.

**Known bug #1: irrelevant bitmask redux.** For 24-bit bitmaps where the “alpha mask” header field is non-zero, stb_image outputs a 32-bit (RGBA) image with the alpha channel set to 255 (fully opaque). Although the input and output images are visually identical, this is not the desired API behavior (as shown by the maintainer having fixed this bug), unnecessarily increases memory usage by one-third, and could cause a buffer overflow if the library user had only allocated enough for memory for a 24-bit image and blindly copied stb_image’s bloated output. We identified this bug because our tree partitioning algorithm grouped the bug-triggering inputs (all but one of the 24-bit Windows 98 bitmaps) into their own leaf. This bug has some overlap with our New bug 2; however, the fix for this bug (as of stb_image 2.25) is highly specific to 24-bit bitmaps and does not address the new bugs discussed previously.

**Classes of detectable bugs.** BIEBER, by design, cannot automatically confirm that a behavior is buggy; strange behaviors can be deliberate “features,” and BIEBER’s decision tree will faithfully replicate them. It does, however, assist with triaging the test cases for manual review, as files with the same behavior/bug will often be handled by the same leaf parser.

BIEBER can help detect bugs that manifest in buggy images being parsed by separate, buggy parser(s) (e.g., in our new bug #2, there was a leaf for Windows 95/98/2000 32-bit bitmaps with an RGBA bitmask). Conceptually, the decision tree has extra leaves for the buggy inputs, where, by some unusual criterion, the buggy inputs are separated from regular inputs. Debugging is simplified because we have both the test case, and the criteria that distinguishes buggy vs. non-buggy inputs.

We can also quickly test the parser decision tree by inspecting the parser’s output for one bitmap corresponding to each leaf. If the bug-triggering inputs are underrepresented in the corpus — likely the case, as the bug would otherwise have already been found through ordinary testing — then inspecting each leaf parser (with one test case each) is much more efficient than randomly sampling input files. The bug-triggering bitmaps for the two new bugs we identified are rare (each ≈ 1% of our bitmap corpus), highlighting both the coverage of our corpus and BIEBER’s sensitivity to bugs.

Two special subclasses of detectable bugs are parsers that violate our high-level model of parsed data structures (that data is hyperrectangular, with dimensions defined by header fields; see new bug #1) and buffer overflows (known bug #1 may lead to this in application code, under some circumstances). These two subclasses result in parsing behavior that is so peculiar that they can often be manually confirmed as bugs, without comparing the output to another parser.

BIEBER does not assist with detecting bugs that manifest in buggy images being parsed by an inappropriate, but preexisting parser (i.e., if the bug has resulted in merged or switched leaves/parsers in the decision tree). However, if these bugs result in buffer overflows, BIEBER will still prevent them by construction in the regenerated parser (as discussed earlier), even if we could not detect them in the original parser.

9 RELATED WORK

9.1 Partial Input Language Specification

Many papers [Blazytko et al. 2019; Comparetti et al. 2009; Cui et al. 2007, 2008; Wang et al. 2011] extract partial input language specifications. Although these have many valuable use cases (e.g.,
intrusion-detection systems, faster fuzzing), they are insufficient for BIEBER’s use case of regenerating parsers that create byte-for-byte identical data structures. For example, in the context of BMP images, a partial specification would roughly be:

- width : offset : length field
- height : offset : length field
- bit-depth : offset : integer (with some constraints)
- pixels : offset : raw data (length = width \times height \times bit depth)

Notably, the pixels field is treated as raw bytes. This is adequate for many fuzzing use cases; the fuzzer would then fill in this field with random byte values to maximize path coverage or similar metrics. Similarly, an intrusion-detection system could use these partial specifications to identify BMP files. However, unlike BIEBER, a “parser” generated from this partial specification does not account for the different types of bitmaps, which each interpret the pixels differently (e.g., 16-bit, 24-bit, 32-bit with various bitmasks, top-down vs. bottom-up, etc.), let alone be able to generate working C or Perl code that can replace the original BMP library, which BIEBER can.

Additionally, it is worth noting that even a complete file format specification (e.g., BMP) is not generally sufficient to regenerate drop-in replacement libraries. The file format specification describes the input format to the library, but the output format of a library is library-dependent. For example, stb_image converts all bitmap images to a top-down representation, even though BMP files are mostly bottom-up [bmp 1995]. However, BMP files are largely stored bottom-up because it is the native representation for Windows APIs, which use a Cartesian-coordinate system; thus, some parsers may prefer to output a data structure that is bottom-up. Similarly, while SndLib’s mus_file_to_float_array function returns all the samples from a single audio channel (e.g., left or right), another library may prefer to keep the original WAV data format, which interleaves samples from the left and right audio channels (L0, R0, L1, R1, ...). BIEBER’s modeling process uses the input/output mappings for the target library, thus its regenerated parsers produce data structures that are byte-for-byte identical to those of the original parsers.

### 9.2 Language and Program Inference

Prior work has extensively studied inference of languages, such as regular and context free languages [Angluin 1987, 1990; De la Higuera 2010; Gold 1978]. Bastani et al. [2017] apply a blackbox approach to inferring programming languages by executing the original program. Höschele and Zeller [2016] use dynamic taint analysis to infer a context free grammar for different input languages. In contrast to these, BIEBER regenerates a parser for binary input formats with non-context-free features such as header-dependent variable-length data segments. Furthermore, BIEBER’s regenerated program does not just accept an input, but also populates the original output data structures.

Caballero and Song [2013], Caballero et al. [2007], and Caballero et al. [2009] propose algorithms (including dynamic-analysis based techniques) to infer the message structure of network protocols. BIEBER also infers the structure of binary formats, but extends this to handle more complex features, such as different WAV/BMP types and variable-length segments.

Gopinath et al. [2020] learn context-free grammars by tracking accesses to the input buffer, as well as the control-flow of the original program, which is assumed to be a stack-based recursive-descent parser. BIEBER’s inferrable file formats (Section 2.1) are not context-free. Furthermore, BIEBER does not use any information about the control-flow information of the original program, nor assume that it is structured in a particular way (as long as it parses the file format correctly).

Program inference shares characteristics with program synthesis, particularly inductive program synthesis (aka programming-by-example) [Polozov and Gulwani 2015; Raza and Gulwani 2018; Singh 2016], which uses example inputs and outputs as a partial program specification. In contrast,
BIEBER assumes we have access to the original application as a form of specification, to produce new executions and rule out incomplete/incorrect parsers.

Helium [Mendis et al. 2015] learns in-memory “stencil kernel” transformations (such as Photoshop’s blur filter) and regenerates them as Halide DSL code, with the aim of higher performance. BIEBER targets input processing code that parses a file into data structure contents, focusing on parser correctness and security. Helium and BIEBER solve some similar problems, such as “buffer structure reconstruction” (including stride detection) and canonicalizing expressions. Helium learns from a single example, while BIEBER integrates the information from multiple examples, with two key corollaries. First, Helium requires that the single input “exercise both branches of all input-dependent conditionals.” If there exists an input-dependent conditional for which no single input will exercise both branches (e.g., in the context of parsers, two different file types), Helium cannot learn it; in contrast, BIEBER can model and regenerate parsers for each example, and unify them into a parser decision tree. Second, to learn input-dependent conditionals, Helium requires that its instrumentation record the branch taken/not-taken information. BIEBER does not; instead, BIEBER infers conditionals by comparing the header bytes between multiple examples.

Active learning has been used in machine learning extensively to improve data efficiency [Settles 2009]. Cambronero et al. [2019] propose a general framework that applies active learning and program inference to learn and regenerate large applications. Our work aligns with this framework, but we present detailed algorithms and a concrete implementation of a prototype (BIEBER), along with empirical evaluation.

Recent developments in program inference have demonstrated the potential for learning non-trivial applications. For example, Shen and Rinard [2019] infer programs that interact with a database by observing the database query and result traffic. Wu [2018] used dynamic analysis to infer a program’s list/map functionality and replace these with a database. Similarly, BIEBER aims to regenerate the full functionality of the original file parsers and does so using dynamic analysis, but BIEBER focuses on file parsing rather than database-related applications.

### 9.3 Secure Parsers

Manually constructed parsers are often implemented as stateful shotgun parsers [Momot et al. 2016], where parsing and input validation functionality is scattered throughout an application, leading to subtle bugs. This phenomenon has been observed in practice and can lead to vulnerabilities [Underwood and Locasto 2016]. Prior work has developed tools to address these difficulties. For example, Nail [Bangert and Zeldovich 2014] is a tool to generate secure data parsers based on a specification, and Caradoc [Endignoux et al. 2016] is a secure PDF parser and validator. BIEBER, in contrast to Nail, does not require the user to write a specification to build a secure parser, but rather infers a parser from the original application’s executions and generates safe-by-construction code. Caradoc’s grammar and rules are hardcoded for PDF, and there is no automatic process for inferring new formats from existing parsers. In contrast to Caradoc, BIEBER has a modeling process and a simple set of primitives that allow it to regenerate parsers for multiple file formats.

### 10 CONCLUSION

We presented BIEBER, the first system to model and regenerate a full working parser from instrumented program executions, producing data structures that are byte-for-byte identical to the data structures in the original program, by Summarizing Loops, Identifying header fields and expressions, Merging parsers into a decision tree, and Emitting hardened code.

Our empirical evaluation demonstrated that BIEBER can efficiently regenerate parsers — while also preventing buffer overflows — for six file formats (waveform audio, MT76x0 .BIN firmware containers, OS/2 1.0 bitmap images, Windows 3.x bitmaps, Windows 95/NT4 bitmaps, and Windows
98/2000 bitmaps), with a target language (C and Perl in our prototype backends\textsuperscript{19}) that need not be the same as the original code. Additionally, BIEBER helped triage two new bugs, and its generated decision tree identified file format predicates that we found to be useful for identifying anomalies in the existing parser and for enhancing our understanding of the file format.

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\textsuperscript{19}We leave JIT compilation — i.e., Just-in-time BIEBER— for future work.
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Appendix A  APPENDICES

A.1  DIODE Expression Denouement

We walk through part of the DIODE expression for extracting a green subpixel from a 16-bit bitmap.  

**Background: 16-bit bitmaps.** 16-bit bitmaps bitpack the red, green, and blue subpixels into two bytes, with 5-bits for each of the colors\(^\text{20}\):

\[
\text{-RRRRRGGGGBBBBB}
\]

Notably, the green subpixel spans both bytes. The goal is to convert the green subpixel into an 8-bit value (ranging from 0 to 255).

**DIODE expression, part 1.** The first step is to read two adjacent bytes from the input file, and combine them into a 16-bit value. This is performed by the following portion of the DIODE expression:

\[
\text{let (} (?x3567}
\text{ (bvshl}
\text{ (( _ zero_extend 24)
\text{ value_0_0x189_0x189))
\text{ (_ bv8 32))
\text{ (( _ zero_extend 24)
\text{ value_0_0x188_0x188)))))}
\]

The first byte (value\_0\_0x188\_0x188\_little; offsets refer to bytes in the input file) contains:

\[
\text{-RRRRRGG}
\]

and the second byte (value\_0\_0x188\_0x189\_little) contains

\[
\text{GGGBBBBB}
\]

The let expression concatenates these bytes into a 16-bit word, using a bitvector shift left ("bvshl") by 8-bits ("bv8") of the second-byte, followed by a bitwise OR ("bvor") with the first-byte. The byte order is reversed due to the little-endian x86 architecture.

The value \(?x3567\) is internally represented as 32-bit\(^{21}\) (to prevent overflow in later steps), which necessitates the explicit zero-extensions because SMT-LIB is strongly typed:

\[
\text{-RRRRRGGGGGGBBBBB}
\]

We now continue with how to extract the green subpixel as an 8-bit value.

**DIODE expression, part 2**

\[
\text{let (}
\text{ (?x3612}
\text{ (bvashr}
\text{ (bvmul}
\text{ (_ bv33 32)
\text{ (bvashr}
\text{ (bvashr}
\text{ (bvand \(?x3567\) (_ bv992 32))
\text{ (_ bv2 32))
\text{ (_ bv3 32)))
\text{ (_ bv2 32)))))
\]

\(^{20}\)BIEBER can also handle variants such as 5-6-5

\(^{21}\)For brevity, we will present them below as 16-bit.
The innermost portion of the expression:

\[(\text{bvand } ?x3567 (_ \text{bv992 } 32))\]

extracts the green subpixel, by performing a bit-wise AND with the bit-vector of value 992 (\text{bv992}; \text{000000111100000} in binary); thus, the expression is equal to:

\[000000GGGG00000\]

The bitvector arithmetic shift right (\text{bvashr}) by 5-bits (in two separate shifts of 3- and 2-bits due to arcane compiler optimizations) results in the bitvector:

\[00000000000GGGGG\]

Notice that the sign-extension arising from the arithmetic (as opposed to logical) shift right is equivalent to zero-extension in this case, since the leftmost bit was zero.

If we directly used the green value, it would range from 0 to 31. A naïve approach of bit-shifting left by 3-bits would result in a range of 0 to 248, which is less than the full range of an 8-bit value (0 to 255). A less naïve approach would therefore multiply by 255 and divide by 31, but that is inefficient. Instead, \text{stb\_image} multiplies by 33, then bit-shifts right by 2-bits, taking advantage of the identity:

\[((\text{unsigned}) (31 * 33) >> 2) = 255\]

This results in:

\[0000000000000000GGGGG\]

\textbf{DIODE expression, part 3}

\(\text{let}\)

\(\{\)

\(\text{(?x481039}

\(\text{ (_ sign\_extend 56)}

\(\text{ (_ extract 7 0) ?x3612))))))\)

The third let expression extracts the eight right-most bits (from indices 0 to 7; note that the high index is listed before the low index), then sign extends it to be a 64-bit value.

\textbf{A.2 Excerpt of DIODE log}

Below is an excerpt of a DIODE log file from running \text{catimg} on a 16-bit bottom-up bitmap, after pre-processing into JSON by their \text{dfsan\_parse} utility. Notice that it is a byte-by-byte dump of the output data structure, using hardcoded input file indices, and lacks any direct information about the looping structure of the input file or output data structure. For example, it is not immediately obvious if any expressions are identical (after abstracting away the concrete input indices denoted by **value...**), nor that the output bytes belong to the same data structure (DIODE can instrument multiple variables/data structures, which are stored in a combined log). For an explanation of the expression field, consult Section A.1 or your local Z3 dealer [De Moura and Bjørner 2008].
(declare-fun **value_0_0x43e_0x43e_little () (_ BitVec 8))
(declare-fun **value_0_0x43f_0x43f_little () (_ BitVec 8))
(declare-fun __dfsan_top_level () (_ BitVec 64))
(assert
(let (((? x226 ( bvsub (_ bv0 32) (_ bv4294967293 32))))
(let ((? x13030 ( bvor ( bvshl
((_ zero_extend 24) ** value_0_0x43f_0x43f_little) (_ bv8 32))
((_ zero_extend 24) ** value_0_0x43e_0x43e_little))))
(let (((? x13047 ( bvashr ( bvmul (_ bv33 32) ( bvashr ( bvshl ( bvand ? x13030 (_ bv31 32)) ? x226 ) (_ bv3 32))) (_ bv2 32)))))
(let ((? x4865826 ( bvand ((_ sign_extend 56)
((_ extract 7 0) ? x13047 )) (_ bv65535 64)))))
(check-sat)"
,"id": 1299951925357182983,
"sink_type": "malloc",
"size": 0,
"stacktrace": [
"/cimg; dfsan_custom.cc@1101:__dfsan_malloc+238595",
"/cimg; useData.h@29:dfs$use_data0+263016",
"/cimg; useData.h@55:dfs$use_data_loop_logged+263681",
"/cimg; sh_image.c@123:dfs$stbi_xload+527240",
"/cimg; sh_image.c@219:dfs$img_load_from_file+534550",
"/cimg:catimg.c@115:main+251177",
"libc.so.6; libc-start.c@291:_libc_start_main+133167",
"/cimg;<invalid>@0:_start+102440"
]
{
"address": 9480882445552,
"constraints": [],
"expression": ";
(set-info :status unknown)
(declare-fun **value_0_0x440_0x440_little () (_ BitVec 8))
(declare-fun **value_0_0x441_0x441_little () (_ BitVec 8))
(declare-fun __dfsan_top_level () (_ BitVec 64))
(assert
(let (((? x13055 ( bvor ( bvshl
((_ zero_extend 24) ** value_0_0x441_0x441_little) (_ bv8 32))
((_ zero_extend 24) ** value_0_0x440_0x440_little))))
(let (((? x13060 ( bvashr ( bvmul ( bvashr ( bvashr
(bvand ? x13055 (_ bv31744 32)) (_ bv7 32))
(_ bv3 32)) (_ bv33 32)) (_ bv2 32)))))

(let ((? x4865828 (bvand ((_ sign_extend 56)
   ((_ extract 7 0) ? x13060)) (_ bv65535 64)))
   (= __dfsan_top_level ? x4865828)))))
(check-sat)"
"id": 1299951925357182983,
"sink_type": "malloc",
"size": 0,
"stacktrace": [
  "catimg; dfsan_custom.cc@1101: __dfsw_malloc+238595",
  "catimg; useData.h@29: dfs$use_data0+263016",
  "catimg; useData.h@55: dfs$use_data_loop_logged+263861",
  "catimg; sh_image.c@123: dfs$stbi_xload+527240",
  "catimg; sh_image.c@219: dfs$img_load_from_file+534550",
  "catimg; catimg.c@0115: main+251177",
  "libc.so.6: libc-start.c@291: __libc_start_main+133167",
  "catimg;<invalid>@0: _start+102440"
],
{
"address": 9480088244552,
"constraints": [ ],
"expression": ";
(set-info :status unknown)"
(declare-fun **value_0_0x440_0x440_little () (_ BitVec 8))
(declare-fun **value_0_0x441_0x441_little () (_ BitVec 8))
(declare-fun _-_dfsan_top_level () (_ BitVec 64))
(assert
(let ((? x13055 (bvor (bvshl ((_ zero_extend 24)
   **value_0_0x441_0x441_little) (_ bv8 32))
   (_ zero_extend 24) **value_0_0x440_0x440_little)))
   (= __dfsan_top_level ? x13055)))))
(check-sat)"
"id": 1299951925357182983,
"sink_type": "malloc",
"size": 0,
"stacktrace": [
  "catimg; dfsan_custom.cc@1101: __dfsw_malloc+238595",
  "catimg; useData.h@29: dfs$use_data0+263016",
  "catimg; useData.h@55: dfs$use_data_loop_logged+263861",
"..."
"catimg;sh_image.c@123:dfs$stbi_xload+527240",
"catimg;sh_image.c@219:dfs$img_load_from_file+534550",
"catimg;catimg.c@115:main+251177",
"libc.so.6;libc-start.c@291:__libc_start_main+133167",
"catimg;<invalid>@0:_start+102440"
],

A.3 Wrapper Function to Read Input (for C Backend)

This function assumes that, once we start calling this function, there will be no intervening fread or fseek operations (this allows avoiding the overhead of calling ftell and fseek). This assumption true for BIEBER’s regenerated parsers, which only perform file reads via this wrapper function.

```c
void readBytesFromFP ( char* buf , FILE* fp , int start , int size ) {
    static long oldPos = -1;
    if ( oldPos == -1) {
        oldPos = ftell (fp);
    }
    if ( oldPos == -1) {
        printf (" Error: oldPos == -1
        abort ();
    }
    if ( oldPos != start ) {
        int sought ;
        sought = fseek (fp , start , SEEK_SET);
        if ( sought != 0) {
            printf (" Unable to fseek to %
                start , sought);
            abort ();
        }
        oldPos = start;
    }
    ssize_t bytesRead = fread (buf , 1, size , fp);
    if ( bytesRead != size ) {
        printf (" Read %
            abort ();
    }
    oldPos = oldPos + bytesRead;
}
```

A.4 Dynamic Array Wrapper Function (for C Backend)

// writeArray : Stores the character into the array at the specified
// index, resizing the array if necessary.
inline void writeArray (unsigned char ** out, long * size, long index, char newValue) {
    if (index < 0) {
        printf("Invalid index %d
", index);
        abort();
    }

    if (index >= *size) {
        if (*size == 0) {
            *out = NULL; // Not guaranteed that it was initialized
        }

        long newSize = *size;
        while (index >= newSize) {
            // Should check when newSize is close to LONG_MAX
            // but on x64 we'll run out of memory before that happens
            newSize = (newSize + 1) * 2;
        }

        *size = newSize;
        assert (size > 0); // Catch wrap-around
        *out = realloc (*out, *size);
        if (*out == NULL) {
            printf("Error: unable to realloc for %d
", index, newValue);
            abort();
        }
    }

    (*out)[index] = newValue;
}

A.5 Algorithms for Consistent Assignments

The steps for rewriting constants as expressions (Section 4.1) and replacing remaining constants with header bytes (Section 4.2) both require an algorithm for finding a set of assignments that are compatible with at least one of the files. BIEBER’s prototype uses a Cartesian product voting algorithm (described in Sectio 4.1), which finds a set of assignments that is compatible with the most files. The Cartesian product algorithm has exponential runtime, but works acceptably in our case studies because of the small number of variables and allowed rewrites. A polynomial-time algorithm would allow BIEBER to scale to larger examples.\footnote{Note that if Cartesian product gets a “better” set of assignments, it might save overall CPU time by not needing DIODE to process as many bytes of input.}

In this section, we present polynomial-time algorithms, some of which produce assignments which, in pilot experiments, were nearly as good as the Cartesian product voting algorithm. We compare the runtime complexity and assignment quality of these algorithms in Figure 9. Note that
we can potentially get tighter runtime bounds by counting the number of candidate assignments (the concatenation of “variable = expression”), which is upper-bounded by \((\#\text{variables}) \times (\#\text{expressions})\).

| Algorithm                          | Runtime       | Quality of Assignments |
|------------------------------------|---------------|------------------------|
| Algorithm 4: Simplest              | \(O(vef)\)   | Meets Basic Requirement|
| Algorithm 5: Improved (conceptual) | \(O((v^2)ef)\) | Better                 |
| Algorithm 6: Improved (optimized)  | \(O((v^2)e + vef)\) | Better                 |
| Cartesian product voting           | \(O((e^o)f)\) | Best                   |

Fig. 9. Comparison of consistent assignment algorithms’ runtime complexity and quality of assignments.

**Simplest.** Randomly pick any one file, which will be designated the “exemplar” file. For each variable, randomly choose any expression that is compatible with the exemplar file. This is guaranteed to produce consistent assignments for at least that exemplar file. We formalize this in Algorithm 4.

**Algorithm 4** Finding a consistent set of files and variable/expression assignments (simplest)

**Input:** A list of files \(F\), a list of variables \(V\), a list of candidate expressions \(E\) that can be assigned to the variables, a matrix of weights \(W\) such that \(W_{f,v,e}\) is zero if file \(f \in F\) is incompatible with assigning expression \(e \in E\) to variable \(v \in V\) and positive otherwise. Files \(f \in F\) do not need to contain all variables \(v \in V\) i.e., \(\sum_{e \in E} W_{0,v,f}\) may equal zero.

**Output:** A non-empty list of compatible \(\text{compatibleFiles} \subseteq F\), and a list \(\text{assignments}\) of 2-tuples \((v \in V, e \in E)\) that fully specify the variables for each compatible file.

**function** CONSISTENT_ASSIGNMENT\((F, V, E, W)\)

```
exemplarFile ← \(F[0]\)            \(\triangleright \) Pick any file
assignments ← \(\emptyset\)
compatFiles ← \(F\)
for \(v \in V\) do
  if \(\sum_{e \in E} W_{0,v,\text{exemplarFile}} \geq 0\) then
    \(e^{\text{OPT}}\) ← argmin\(e \in E\) \(W_{0,v,\text{exemplarFile}}\) \(\triangleright \) Any \(e\) that works with \(v\)
    assignments ← assignments + \((v, e^{\text{OPT}})\)
    for \(f \in \text{compatFiles}\) do \(\triangleright \) Remove any files that are incompatible with the assignment
      if \(W_{f,v,e^{\text{OPT}}} = 0\) then
        compatFiles ← compatFiles \(\backslash f\)
    end if
  end for
end if
return (compatFiles, assignments)
end function
```

**Improved (conceptual).** Algorithm 5 shows the conceptual algorithm for calculating consistent assignments. Initially, all files are compatible and all variables are unassigned. At each loop iteration, we select, from all expressions and the unassigned variables, the assignment (variable = expression) that has the total most weight across all compatible files. We then consider the variable assigned, and delete any files that are not compatible with this new assignment.

**Improved (optimized).** There are two expensive steps in Algorithm 5, which scan across the entire 3D array:
Algorithm 5 Finding a consistent set of files and variable/expression assignments (conceptual)

Input: As per Algorithm 4
Output: A non-empty list of compatibleFiles \( \subseteq F \), and a list assignments of 2-tuples \((v \in V, e \in E)\) that fully specify the variables for each compatible file.

function CONSISTENT_ASSIGNMENT\((F, V, E, W)\)

\[
\text{assignments} \leftarrow \emptyset \\
\text{compatFiles} \leftarrow F \\
\text{unassignedVars} \leftarrow V \\
\text{while } \sum_{f \in \text{compatFiles}, v \in \text{unassignedVars}, e \in E} W_{v,e,f} > 0 \text{ do} \\
\quad (v^{OPT}, e^{OPT}) \leftarrow \text{argmax}_{v \in \text{unassignedVars}, e \in E} \sum_{f \in \text{compatFiles}} W_{v,e,f} \\
\quad \text{assignments} \leftarrow \text{assignments} + (v^{OPT}, e^{OPT}) \\
\quad \text{unassignedVars} \leftarrow \text{unassignedVars} \setminus v^{OPT} \\
\quad \text{for } f \in \text{compatFiles} \text{ do} \\
\qquad \text{if } W_{v^{OPT}, e^{OPT}, f} = 0 \text{ then} \\
\qquad \qquad \text{compatFiles} \leftarrow \text{compatFiles} \setminus f \\
\quad \text{end if} \\
\text{end for} \\
\text{end while} \\
\text{return } (\text{compatFiles}, \text{assignments})
\]

end function

\[\sum_{f \in \text{compatFiles}, v \in \text{unassignedVars}, e \in E} W_{v,e,f}\]
and
\[\text{argmax}_{v \in \text{unassignedVars}, e \in E} \sum_{f \in \text{compatFiles}} W_{v,e,f} .\]

We observe that we can compute these quantities using a 2D array, where we have summed across the file dimension. This requires careful bookkeeping to update this 2D array whenever we remove a variable from the list of unassigned variables, or remove a file from the list of compatible files, but avoiding deleting the weight of a value twice \(i.e.,\) once because the variable was assigned, and again if from an incompatible file. We present this in Algorithm 6.

Complexity analysis of Algorithm 6. Assume each file has the same number of variables and candidate expressions.

1. Initial nested for loops to pre-calculate assignmentWeights and assignmentsPerFile: \(O(vef)\)
2. Main while loop: We eliminate at least one variable per iteration, hence there are at most \(v\) iterations. Cost per iteration:
   - Find the assignment \((v^{OPT}, e^{OPT})\) with the highest frequency: \(O(ve)\)
   - Update compatibleFiles: \(O(f)\)
   - Update assignmentWeights to delete \(v^{OPT}\): \(O(ef)\)
   - Update assignmentWeights to remove any incompatible files: amortized \(O(ve)\). Although this step is worst-case \(O(vef)\), each incompatible file is processed only once in total across the \(v\) loops.

The total cost of Algorithm 6 is: \(O(vef) + v*(O(ve)+O(f)+O(ef)+O(f)+O(ve)) = O((v^2)e+vef)\)
Algorithm 6 Finding a consistent set of files and variable/expression assignments (optimized)

Input: As per Algorithm 4, except that we instantiate $W$ as nested hashtables.

Output: As per Algorithm 5

function $\text{Prune}(v, e, f, W, \text{assignmentWeights})$

$\text{assignmentWeights}[v : e] \leftarrow \text{assignmentWeights}[v : e] - W[v][e][f]$

if $\text{assignmentWeights}[v : e] = 0$ then

$\text{delete assignmentWeights}[v : e]$

end if

end function

function $\text{ConsistentAssignment}(F, V, E, W)$

$\text{compatibleFiles} \leftarrow \emptyset$  \quad \text{\# Place array in outer scope so that we can return it}

$\text{assignmentWeights} \leftarrow \emptyset$, $\text{assignmentsPerFile} \leftarrow \emptyset$

for $v \in V$ do  \quad \text{\# Precompute summations of 3D-array}

for $e \in (\text{keys } W[v])$ do

for $f \in (\text{keys } W[v][e])$ do

$\text{assignmentWeights}[v : e] \leftarrow \text{assignmentWeights}[v : e] + W[v][e][f]$

$\text{assignmentsPerFile}[f][v : e] = 1$

end for

end for

end for

$\text{assignments} \leftarrow \emptyset$, $\text{assignedVariables} \leftarrow \emptyset$

$\text{remainingFiles} \leftarrow F$  \quad \text{\# We ping-pong between shrinking this and $\text{compatibleFiles}$}

while $|\text{assignmentWeights}| > 0$ do

$(v^{\text{OPT}}, e^{\text{OPT}}) \leftarrow \text{argmax}_a \text{assignmentWeights}[a]$  \quad \text{\# Recalculate which subset of $\text{remainingFiles}$ are compatible}

$\text{assignments} \leftarrow \text{assignments} + (v^{\text{OPT}}, e^{\text{OPT}})$

$\text{compatibleFiles} \leftarrow \emptyset$

for $f \in (\text{keys } W[v^{\text{OPT}}][e^{\text{OPT}}])$ do

if $f \in \text{remainingFiles}$ then

$\text{compatibleFiles}[f] \leftarrow \text{True}$

end if

end for

for $e \in (\text{keys } W[v^{\text{OPT}}])$ do  \quad \text{\# We’ve assigned $v^{\text{OPT}}$; remove it from assignmentWeights}

for $f \in (\text{keys } W[v^{\text{OPT}}][e])$ do

if $\text{compatibleFiles}[f]$ then

$\text{Prune}(v^{\text{OPT}}, e, f, W, \text{assignmentWeights})$

end if

end for

end for

for $f \in \text{remainingFiles}$ do  \quad \text{\# Handle any remainingFiles that are not compatible}

if not $\text{compatibleFiles}[f]$ then

$\text{remainingFiles} \leftarrow \text{remainingFiles} \setminus f$

for $(v, e) \in (\text{keys } \text{assignmentPerFile}[f])$ do

if not $\text{assignedVariables}(v)$ then  \quad \text{\# Don’t prune: already pruned early}

$\text{Prune}(v, e, f, W, \text{assignmentWeights})$

end if

end for

end if

end for

$\text{assignedVariables}[v^{\text{OPT}}] \leftarrow \text{True}$

end while

return $(\text{compatibleFiles}, \text{assignments})$

end function