Fine-Grained Library Customization

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Abstract

Code bloat widely exists in production-run software. Left untackled, it not only degrades software performance but also increases its attack surface. In this work, we conduct a case study to understand this issue in statically linked libraries. To be specific, we analyze midilib, a software package enclosing statically linked libraries. We show that it is possible to leverage dependence analysis to trim the resultless code statements residing in a target library. With this observation, we believe it is possible to build a tool to automatically cut off code pertaining to resultless operations.

1 Introduction

Modular design is widely used in traditional software development to control the implementation complexity [17]. After dividing a large program into smaller modules or libraries, developers can focus on their own parts and implement desired functionalities. To improve development productivity, libraries are encouraged to be reusable and to be shared by different programs [15]. Therefore, libraries tend to have generic interfaces and provide different functionalities for various usage scenarios.

When a library is used by a program, it is usually statically linked to that program. Since the program only has limited calling contexts and usage scenarios, more-than-necessary code inside the library is linked, causing code bloat [14]. Bloated code widely exists in production-run software. For example, a recent study shows that only around 20% instructions of Firefox are executed under typical workloads [10].

Bloated code can lead to various problems. First, it potentially introduces more bugs and vulnerabilities. A recent study has showed that most vulnerabilities in protocol implementation reside in modules not widely used [5]. Second, a larger code size increases memory pressure and causes cache misses when loading instructions [11]. Third, bloated code incurs resultless or redundant computation, resulting in computation inefficiency [2, 20, 21]. Last but not least, a larger code size also consumes network bandwidth when being distributed across the Internet [11, 12].

Inspired by this, we propose to address the code bloating problem by performing library customization against statically linked libraries. Different from previous works on detecting runtime bloat [2, 3, 9, 19–21] or library customization [5–8, 11–13], our technique is a fine-grained code removal scheme built on the basis of the following hypothesis. Many library functions return its computation results as a data object defined by a “struct”. However, it is typical the case that many fields in the struct are not in use by the upper level applications. This means that there must be resultless computation residing in the library and we have the potential to trim the code pertaining to the resultless computation.

To validate our hypothesis, we conduct a case study against a software package which contains statically linked libraries. We show that a library returns a data object with 44 primitive fields. However, upper level software only uses 9 of them. By using dependence analysis along with two code trimming schemes, we can reduce the code space of the library by about 50%. Given that many software contain statically linked libraries, we believe this observation and practice could be potentially generalized and significantly benefit library customization.

The rest of the paper is organized as follows. In Section 2 we discuss our case study against a software package and describe two proof-of-concept techniques. In Section 3 we discuss the works relevant to library customization. In Section 4 we conclude our paper and discuss future works.

2 Case Study

As is mentioned above, a shared library statically linked might contain many resultless operations that can be potentially trimmed. In this section, we illustrate this practice by taking for example midilib [4] an open-source repository in C.

Midilib contains an implementation of I/O libraries for MIDI files [16] in midifile.c. It also provides other functionalities. After building midilib, we can obtain five executables, which are m2rtttl, to convert MIDI files to RTTTL [18], mididump, to dump MIDI file content, mfc120, to change MIDI file version, mozart, to generate simple musics, and miditest, to conduct tests. The compiled object file of midifile.c is statically linked to every executable. Thus, each executable contains the same library.

In the following, we first perform simple code analysis against the aforementioned software and thus reveal
while(midiReadGetNextMessage(mf, &msg)) {
    switch(msg.iType) {
    case msgNoteOff:
        iCurrPlayingNote = -1;
        iCurrPlayStart = msg.dwAbsPos;
        break;
    case msgNoteOn: ...
        break;
    case msgMetaEvent: ...
        break;
    default: /* Ignore other cases */
        break;
    }
}

Table 2: The code fragment of struct MIDI_MSG.

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by the upper level of the application. For the remaining
1700 write operations, we partition them into two cate-
gories. In the first category, we observe that, there are
1015 write operations (about 60%) that neither the lower
level of the library nor the upper level of the application
read the fields tied to these operations, which implies that
we can safely trim these operations and thus reduce the
code space of the library. In the second category indi-
cated by the remaining 685 write operations (approximately
40%), we note that, while the fields tied to these
operations are not read by the upper level of the applica-
tion, they are involved in data dependency in lower level
of the library. Admittedly, this does not mean we cannot
remove these operations. But it implies that we have to
trim these operations with the consideration of data de-
pendency.

2.2 Customization Demonstration

Based on the analysis and observation above, we design
and develop two simple tools using LLVM to customize
the lower level of the library or more precisely speaking
the function midiReadGetNextMessage implemented in the library. In the following, we describe them in turn.

Tool for Eliminating Resultless Field Assignments. As
is mentioned above, if the value assigned to a field is
not accessed by the upper level of the application nor
the lower level of the library, then we could safely re-
move the statements tied to such assignment. Inspired
by this observation, we develop a tool to identify and cut
off such code statements.

To be specific, we first leverage the strict layout informa-
tion provided by LLVM to compute the offsets of the
fields that neither the library nor the application reads.
Then, using this information, we pinpoint those assign-
ment instructions (i.e., LLVM intermediate code) corre-
sponding to these fields. Since the assignment instruc-
tions represent the site of assigning a value to a field, and
operations pertaining to such sites also contain those in-
structions that compute the assigned value and the field
address, we finally perform a simple data dependence
analysis to further identify the instructions relevant to
the field assignment. In this preliminary work, we deem
such instructions as unnecessary and our tool trim these
instructions along with those tied to resultless value as-
signments.

In the implementation of the library function midiReadGetNextMessage, our tool tracks down 4
fields, the read of which neither presents in the library
nor the upper level of the application. These 4 fields as-
sume with 51 instructions in the library, counting for
about 7% (51 out of 722) LLVM intermediate code that
we can safely eliminate. It is not difficult to note, as is
mentioned in Section 2.1, we have identified only 9 fields
that the upper level of the application reads, but our tool
tracks down only 4 fields, the read of which are not pre-

tened in the application. Here, the reason is as follows.

As is illustrated in Figure 2, many primitive fields are
enclosed in the union type field MsgData. From the
perspective of LLVM, this means that the machine uti-
izes the same memory location to store different struct
fields, such as NoteOff, NoteOn, NoteKeyPressure,
and so on. In our implementation, our tool distin-
guishes primitive fields based on their offsets. This
means it lacks the ability to distinguish the prim-
itive fields referred by the union struct, such as
failing to differ msg.MsgData.NoteOn.iNote from
msg.MsgData.NoteOff.iNote. Therefore, our current
results miss to pinpoint some primitive fields that neither
the library nor the application reads.

Tool for Eliminating Unused Packet Types. Recall that
in addition to leveraging resultless field assignments for
library code customization, we can use the packet type
information as an indicator to identify resultless oper-
ations in the library. Motivated by this observation, we de-
sign and develop another tool that takes advantage of this

```c
/* midifile.c */

BOOL midiReadGetNextMessage(..., MIDI_MSG *msg)
{  
  ...
  switch(msg.iType) {
  case msgNoteOn:  
    msg->MsgData.NoteOn.iChannel = ...;  
    msg->MsgData.NoteOn.iNote = ...;  
    msg->iMsgSize = 3;  
    break;
  case msgNoteOff: ...
    break;
  case msgNoteKeyPressure:
    msg->MsgData.NoteKeyPressure.iChannel = ...;
    msg->MsgData.NoteKeyPressure.iNote = ...;
    msg->MsgData.NoteKeyPressure.iPressure = ...;
    msg->iMsgSize = 3;  
    break;
  case msgGetParameter: ...
    break;
  case msgSetProgram: ...
    break;
  case msgChangePress: ...
    break;
  case msgSetPitchWheel: ...
    break;
  case msgMetaEvent: ...
    break;
  case msgSysEx1:
    ...
    break;
  case msgSysEx2: ...
    break;
  }
  ptr += msg->iMsgSize
  ...
  }
```

Table 3: The code fragment of the library function
midiReadGetNextMessage.
observed affection and performs library code customization.

As is shown in Table 3, the library assigns a value to a field (e.g., msg.MsgData.NoteKeyPress.iChannel) in line 13 only after it reads another field (e.g., msg.iType in line 4) and a certain condition holds (e.g., msg.iType == msg.NoteKeyPress in line 5). Intuition suggests this can be interpreted as a control dependency. In the higher level of the application, as is shown in Table 1, we do not observe the same control dependency relationship. This means that the corresponding computation in the library (i.e., the statements in line 13-15) has no effect upon the upper level of the application. We could leverage this mismatched pattern to cut off the code fragment accordingly and thus reduce the code size of the library.

It should be noted that we do not trim the statements in line 16-17 nor that in line 12 depicted in Table 1 because – as specified in line 32 – the global variable ptr is dependent upon iMsgSize.

In this work, we implement this pattern matching approach using LLVM. By performing code customization against the aforementioned library through the patterns identified, we track down 33 field assignment instructions in the library that do not have impact to the upper level of the application. Following the procedure used in the first tool mentioned above, we also use data dependence analysis to pinpoint other statements pertaining to those tied to resultless filed assignments. Together with the 33 resultless instructions, in total, we pinpoint 355 out of 722 LLVM instructions that can be safely eliminated.

Going beyond testing the tools individually, we further combine the unnecessary instructions obtained from both aforementioned tools. We observe the combined techniques can identify 36 resultless field assignments in total. Using data dependence analysis, they lead up to the removal of 367 LLVM instructions, accounting for 50.83% of instructions removal (i.e., 367 out of 722). We have already noted that these about 50% of instructions removal reflect approximately 39.63% lines of source code removal. This indicates the potential of fine-grained library customization.

3 Related Works

Code bloat [14] refers to unnecessarily large code size, which can increase security attack surface, consume more memory, lower instruction cache performance, and even make the distribution of software more difficult. There are empirical studies that confirm the existence of code bloat and its negative impact. Quach et al. [10] conduct an empirical study to understand how much unused code in different types of programs. The authors propose two methods to measure the size of unused code, one is to identify function calls isolated from call graph statically, and the other is to dynamically profile how many instructions are not executed under typical workloads. The authors report that a large portion of code is not executed in the investigated programs. Hong et al. [5] study 20 vulnerabilities related to protocol implementation, and finds that most of the vulnerabilities reside in code implementation not commonly used. Customizing protocol implementation can successfully eliminates most of these vulnerabilities.

Researchers and practitioners build many techniques to identify and eliminate unnecessary functionalities [5, 6, 11-13]. LDoctor [13] identifies inefficient loops conducting resultless computation and suggests developers remove these loops conditionally or unconditionally. Hong et al. [5] proposes a feature access control system to unify protocol implementation customization, which can remove unnecessary features in protocol implementation and reduce attack surface. Application containers usually contain unneeded files. As a dynamic technique, Cimplifier [11, 12] can automatically detect unnecessary resources through analyzing system calls. JRed [8] detect unused classes and methods using reachability analysis after building call graphs for programs to be customized. Jiang et al. [6, 7] propose a technique to cut user-specified functions through backward and forward slicing. Although useful, these techniques work on code granularities much larger than our proposed techniques, such as loops or files. These techniques do not target to eliminate fine-grained resultless computation.

4 Conclusion and Future Work

In this paper, we perform a code analysis against a library statically linked to a target executable. We show that using the fields in a data structure we can potentially trim the code statements resultless for the upper level of applications, and thus potentially reduce the attack surface of the library. Using two proof-of-concept tools designed and developed based on our analysis, we demonstrate the possibility of performing fine-grained customization for a library.

As future work, we will extend our techniques from the following aspects. First, we plan to examine more libraries and conduct an empirical study to understand root causes of resultless field assignments and their impact in the real world. Second, we plan to build a robust static technique and explore different design points during technical design. Third, we plan to build an automated testing platform combining static and dynamic analysis to test customized libraries.
References


