`DeClassifier`: Class-Inheritance Inference Engine for Optimized C++ Binaries

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***Abstract*—Recovering class inheritance from C++ binaries has several security benefits including problems such as decompilation and program hardening. Thanks to the optimization guidelines prescribed by the C++ standard, commercial C++ binaries tend to be optimized. While state-of-the-art class inheritance inference solutions are effective in dealing with unoptimized code, their efficacy is impeded by optimization. Particularly, constructor inlining–or worse exclusion– due to optimization render class inheritance recovery challenging. Further, while modern solutions such as MARX can successfully group classes within an inheritance sub-tree, they fail to establish directionality of inheritance, which is crucial for security-related applications (e.g. decompilation). We implemented a prototype of `DeClassifier` using Binary Analysis Platform (BAP) and evaluated `DeClassifier` against 16 binaries compiled using gcc under multiple optimization settings. We show that (1) `DeClassifier` can recover 94.5% and 71.4% true positive directed edges in the class hierarchy tree under O0 and O2 optimizations respectively, (2) a combination of ctor+dtor analysis provides much better inference than ctor only analysis.**

***Index Terms*—Class hierarchy recovery, software reverse engineering**

I. INTRODUCTION

Recovery of class inheritance of a C++ program is useful in many ways, and often necessary. While extracting class hierarchy from source code is straightforward (e.g., class-hierarchy analysis [2], [10], [11], [14], [17], [25], [27]), recovering class hierarchy from a binary is hard [21], [23], but useful. For example, any attempt at C++ program decompilation must infer at least a partial class hierarchy from a binary [7], [8]. Similarly, defenses that enforce strict control-flow integrity (CFI) policies on C++ binaries rely on class hierarchy analysis (e.g., Marx [18], VCI [6]).

Although RunTime Type Information (RTTI), a per-class type-revealing data structure may be present in certain C++ programs, it is often absent in COTS binaries. On the one hand, RTTI structure contains information about the parents of a given polymorphic class, which can be used to reliably reconstruct the class hierarchy of a program. But on the other hand, use of RTTI is discouraged in commercial code due to the high runtime overhead imposed by operators (i.e., `dynamic_cast` and `typeinfo`) that use RTTI. In fact, most commercial-off-the-shelf (COTS) are closed source and do not contain RTTI in the binary. Without RTTI, inferring class hierarchy (inferring high level semantics in general) from COTS C++ software poses multiple challenges. First, most solutions (e.g., VCI [6], SmartDec [7], [8], HexRays Decompiler [23]) heavily rely on constructor analysis due to the well-defined inheritance-revealing control flow during construction of a C++ object.

Optimization is common in C++ code, yet poses a serious impediment to class inheritance inference. First, as a fundamental problem, constructor analysis suffers from low precision and is often insufficient. This is because COTS C++ binaries are often optimized and tend to have many inlined functions including inlined constructors. In fact, per ISO C++ 7.1.2/3—"*A function defined within a class definition is an inlined function*". Second, aggressive compiler optimization often results in exclusion of key functions (e.g., constructors) and/or entire classes from the binary, which makes inference hard. For example, when a most derived class is not instantiated, the compiler may conveniently exclude such class definitions from the binary. In fact, we consistently found a significant reduction in the number of constructors in the binary with higher levels of optimizations (see Table IX in Appendix C). Finally, it is hard to discern inherited relationship (e.g., class A inherits from class B) from composed relationship (e.g., class A contains an object of class B)–specially in the case of optimized code.

These challenges are evidenced in most relevant recent works VCI [6] and Marx [18]. These efforts employ class hierarchy analysis on C++ binaries without relying on RTTI. On the one hand, VCI's precision and accuracy are largely dependent on constructor identification, which in turn is heavily impeded by inlined or missing constructors. On the other hand, Marx acknowledges the difficulty imposed by optimization and inlining, and limits its scope to identifying class membership to inheritance trees without actually recovering a directed class inheritance tree. As a fundamental problem, aggressive compiler optimizations are common in COTS binaries, and pose complex challenges that state-of-the-art C++ binary analysis solutions are unable to handle.

In this paper, we present `DeClassifier`, a robust class hierarchy inference engine for C++ binaries. `DeClassifier` employs static analysis and is built on top of BAP [3]. Unlike prior efforts, we support optimized code, which is common in COTS C++ programs. As a key distinction, our inference engine is based on code features that *can not* be optimized away (i.e., eliminated) during compile time. As such, these features form robust inference points. `DeClassifier` incorporates multiple novel analysis techniques in order to handle optimized code including inlined and missing constructors. This makes `DeClassifier` apt for COTS binaries. First, we take advantage of the fact that destructors tend to be virtual in COTS code as they help avoid memory leaks. Because calls to virtual functions can not be statically resolved, compilers can not inline virtual functions during compile time, and retain them in the binary without inlining their code at the callsites. Therefore, in comparison with constructors that are non-virtual, destructors in a binary tend to be more in number. `DeClassifier` employs a *constructor-destructor* combination approach to achieve optimal recovery. Second, because virtual functions must be retained in the binary, we employ inter-procedural object-layout analysis on virtual functions to construct an object model for each class and use it to recover inheritance relationship from functions with inlined constructors or inlined destructor, also eliminating false positives in inheritance relationship. We are the first to do this. Finally, we identify precise points of completion of object construction in order to distinguish between composed and inherited objects. To the best of our knowledge, this the first effort to effectively handle optimized C++ binaries commonly found in COTS software.

Full CHT recovery is hard: In general, recovering C++ semantics from optimized binaries is hard. Although `DeClassifier` employs multiple novel techniques to handle optimized code, C++ compilers eliminate entire classes from the binary—if the classes are deemed to be unnecessary (e.g., through dead code elimination) during compilation. In such cases, `DeClassifier` misses classes that have no remnants in the binary. Even so, to the best of our knowledge, `DeClassifier` is the only *practical* solution that can effectively infer *directed* class inheritance tree from optimized code.

Our contributions can be summarized as follows:

- We present `DeClassifier`, an inference engine for recovering class hierarchy information from optimized C++ code.
- We employ multiple novel analysis techniques including *constructor-destructor* analysis, inter-procedural object layout analysis, and precise identification of object completion. These techniques allow `DeClassifier` to handle optimized code including inlined or missing constructors, distinguish between constructors and non-virtual destructors, and decipher between composed and inherited objects. The idea of extracting class hierarchy from both constructors and destructors have been considered previously [8], however, for optimized code, we are the first to highlight the effectiveness of destructor analysis over constructor analysis.
- We evaluate `DeClassifier` on 16 binaries. On average we are able to recover significant part of the inheritance graph correctly. Specifically, 94.5% (recall) of edges under O0 and 71.4% (recall) of edges under O2.

The rest of the paper is organized as follows. In Section II, we provide the technical background required to understand the rest of the paper. In Section III we present the key challenges and an overview of our solution. Section IV presents the technical details of `DeClassifier`. We evaluate in Section V, discuss in Section VI, present related work in Section VII, and finally conclude in Section VIII.

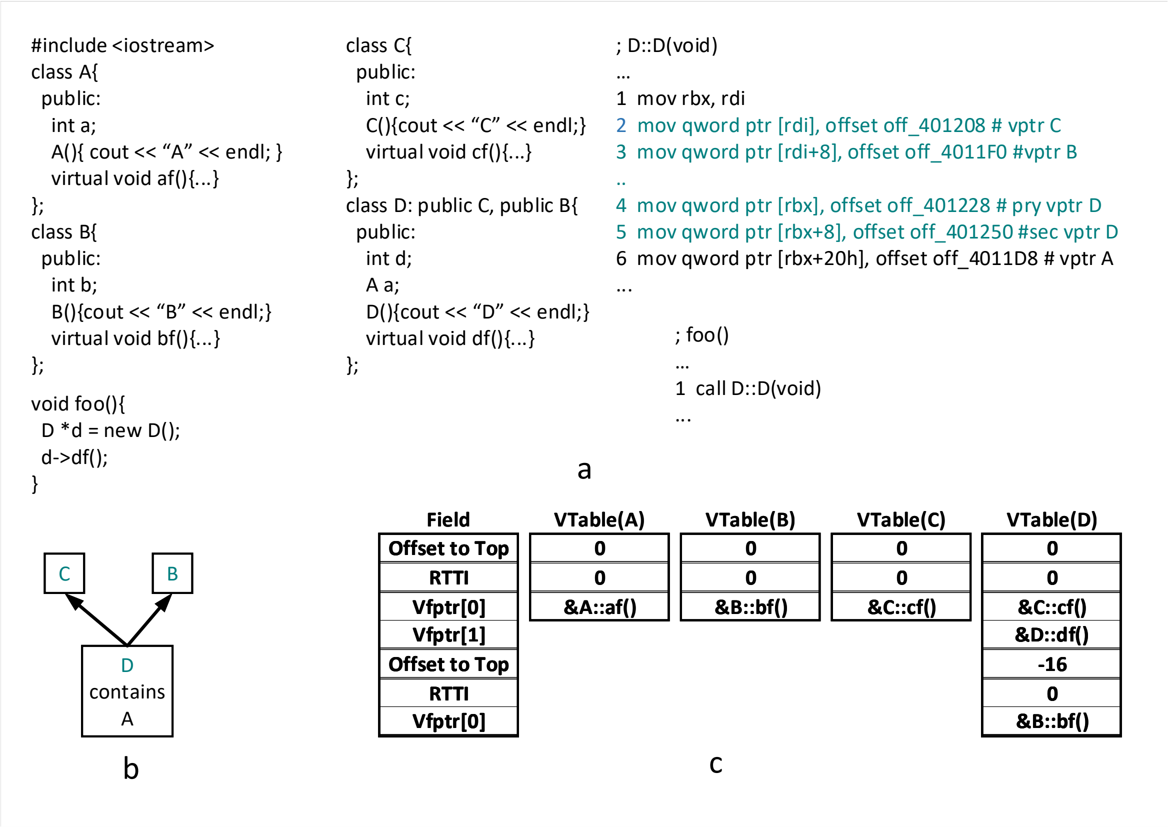
II. TECHNICAL BACKGROUND

A. Implementation of Polymorphism and Inheritance in C++

In order to implement polymorphism, C++ compilers utilize a per-class supplementary data structure called "VTable". The structure of the VTable is dictated by the C++ ABIs—Itanium [1] and MSVC [20]. A VTable is allocated for each polymorphic class (i.e., a class with virtual functions, or inherits from class(es) with virtual function, or inherits a class virtually). Each VTable contains an array of function pointers representing the polymorphic functions that the object of a given type can invoke at runtime. In order to prevent corruption, the VTables are allocated in the read-only sections of a binary. Each object of a polymorphic class contains an implicit pointer to the VTable (vptr) as the first member variable. Within the constructor of a polymorphic class, the vptr is initialized to point to the VTable for the type of the object being constructed. Among other fields, each VTable contains 3 mandatory fields—*OffsetToTop*, pointer to *TypeInfo* (also called RunTime Type Information or RTTI), and an array of virtual function pointers or vfptrs. Although RTTI is a mandatory field, a NULL value is used to signify its exclusion during compilation. In the past, mandatory fields have been used as a signature for identification of VTables in the binary [19].

In case of multiple inheritance, wherein a class derives from more than one polymorphic base class, the VTable for derived class comprises of a group of 2 or more VTables—a primary and one or more secondary VTables depending on the number of secondary bases. The derived class and its primary base class share the primary VTable, and each secondary base class is allocated a secondary VTable. Further, the derived object and the primary base sub-object share the same base address, and each secondary base sub-object is found at an offset from the derived object base address. The VTable group comprising of the primary and secondary VTables is collectively called "complete-object VTable".

The OffsetToTop field indicates the displacement that must be added to the sub-object within a derived object to reach the base of the derived object. If the RTTI value is not null, the RTTI pointers for all the VTables within a complete-object VTable point to the same RTTI structure. For the running example in Figure 1, the complete-object VTable for D comprises of a primary VTable with 2 virtual function pointers, and a secondary VTable with one virtual function pointer. The secondary VTable contains an OffsetToTop value (-16) that must be added to the sub-object B-in-D to reach the base of D. For more information on each of the fields and other optional fields in the VTable, we refer readers to the ABI [1].



```
#include <iostream>
class A{
  public:
    int a;
    A(){ cout << "A" << endl; }
    virtual void af(){...}
};
class B{
  public:
    int b;
    B(){cout << "B" << endl;}
    virtual void bf(){...}
};

void foo(){
  D *d = new D();
  d->df();
}
```

```
class C{
  public:
    int c;
    C(){cout << "C" << endl;}
    virtual void cf(){...}
};
class D: public C, public B{
  public:
    int d;
    A a;
    D(){cout << "D" << endl;}
    virtual void df(){...}
};
```

```
; D::D(void)
...
1  mov rbx, rdi
2  mov qword ptr [rdi], offset off_401208 # vptr C
3  mov qword ptr [rdi+8], offset off_4011F0 #vptr B
..
4  mov qword ptr [rbx], offset off_401228 # pry vptr D
5  mov qword ptr [rbx+8], offset off_401250 #sec vptr D
6  mov qword ptr [rbx+20h], offset off_4011D8 # vptr A
...
```

```
; foo()
...
1  call D::D(void)
...
```

a

b

Field	VTable(A)	VTable(B)	VTable(C)	VTable(D)
Offset to Top	**0**	**0**	**0**	**0**
RTTI	**0**	**0**	**0**	**0**
Vfptr[0]	**&A::af()**	**&B::bf()**	**&C::cf()**	**&C::cf()**
Vfptr[1]				**&D::df()**
Offset to Top				**-16**
RTTI				**0**
Vfptr[0]				**&B::bf()**

c

Fig. 1: Running example comprising classes A, B, C and D, and corresponding VTable layout when compiled using g++ with flag `-fno-rtti`. Note: 'pry' means primary, and 'sec' means secondary.

B. Construction and Destruction

Constructor and destructor are called when an object of a class is created and destroyed respectively. Each class may contain one or more constructors and a single destructor. If no constructor is defined by the developer, a default constructor will be provided by the compiler. During construction, constructors of base classes first get invoked, starting from the primary base. The address of the subobject being constructed is passed as an argument. Then the vptr(s) of the object being constructed is assigned into appropriate offset(s). Finally, member variables including composed members are constructed. Similarly, during object destruction, vptr of the object gets assigned. Then member variables including composed member objects are destroyed. Finally, destructors of immediate bases are invoked, starting from the primary base. Again, the address of the subobject being destroyed is passed as an argument.

As a part of the construction and destruction of member variables, constructors and destructors may themselves invoke virtual functions. Therefore assignment of vptr occurs before the respective initialization/finalization of member variables. Note that the constructors and destructors of each base class write their own set of vptrs in appropriate locations in the object, which get overwritten by subsequent classes in the inheritance chain. For example, in Figure 1, object D shares its base with subobject C-in-D (because C is the primary base of D). All the subobject constructors C() and B(), and composed object constructor A() are inlined in derived object constructor D(). Instruction 2 writes vptr of C-in-D with address of VTable of C, which is then overwritten by instruction 4 that writes vptr of D with address of VTable of D.

C. Virtual Destructors

Unlike constructors, destructors in C++ can be–and often are–declared as virtual. It may sometimes be necessary to delete a derived class object that is referenced through a base class pointer. The C++ standard states that deleting an object of derived class through a pointer to its base class that has non-virtual destructor leads to undefined behavior (see paragraph 3 in ISO/IEC 14882-2014). Therefore, it is common practice to mark destructors as virtual, which forces runtime resolution of the virtual call to the correct derived class destructor. These destructors must therefore be retained in the binary and destructor code can not be inlined at the deletion site. As shown in Table IX (Appendix C), the binary usually contains more destructors than constructor.

III. SOLUTION OVERVIEW

A. Key Challenges

a) C1: Constructor Inlining: Compilers inline functions by replacing the callsite with the body of the called function.

Virtual function callsites cannot be inlined since the exact function to call is only known at runtime depending on the object type. However, because constructors can not be virtual, their calls are statically resolved and inlined when possible. In fact, we found this to be very common and prescribed by the C++ standard (see ISO C++ 7.1.2/3). Any function defined within a class definition will be inlined as a default behavior. This is a challenge since state-of-the-art class hierarchy recovery tools like VCI [6] depend primarily on the identification of constructors. Constructor inlining gives rise to two problems:

- *Missed base class constructor calls*: Consider the running example in Figure 1 where the primary and secondary base class constructors of D are inlined on lines 2 and 3 respectively. As detailed in section II-B, in a constructor, the composed class' constructor get called after the vptrs of the owner class have been initialized. Therefore, in order not to include composed classes in a given class hierarchy, VCI looks at the first primary vptr initialization to an object address which appears on line 2 and concludes that the constructor belongs to the class with primary vptr 0x401208 (i.e., C instead of D), subsequent constructor calls are ignored. As such it fails to identify any relationship between D and C or D and B. Overwrite analysis adopted by Marx will be able to group the primary vptr of D with the primary vptr of C as well as the secondary vptr of D with the primary vptr of C, however, it cannot differentiate the derived class from the base class.
- *False constructor identification*: In higher levels of optimization, the compiler could inline entire constructor D() in the instantiating function `foo`. Therefore, although not a constructor, `foo` would contain the vptr initialization. In order to accommodate inlining, VCI identifies constructors by simply looking for vptr initialization (not requiring that the vptr is written into the first entry of an object address) which would result in falses (see Section 4.2 in [6]). If `foo` calls other functions which also contain inlined constructors, a false relationship is inferred between the vptrs these non-constructor functions initialize.

b) C2: Inheritance vs Composition: Failure to correctly differentiate the base class constructors (or destructors) from those of member classes will result in false inheritance inference between a class and its member classes. VCI partially handles this by considering only constructor calls that happen before initialization of the primary vptrs, however, this works only for constructors but not destructors, this is because the derived class vptrs get written first. A more general approach is required to differentiate composed and inherited objects for constructors or destructors irrespective of whether or not they are inlined.

c) C3: Missing Constructors: Another outcome of compiler optimization is complete removal of constructors. Note that this is a different problem from function inlining. A virtual function is guaranteed to be in the binary as long as the VTable it belongs to is present. In fact, we found that significant number of constructors are optimized-out during compilation, and their definitions are excluded from the binary (see Table IX Appendix C).

B. Scope and Assumptions

Our primary goal is to leverage multiple binary-level features to reconstruct polymorphic non-virtual class inheritance tree from COTS binaries—even in an optimized setting. We target COTS C++ binaries which might have been compiled with high levels of optimization and with no debugging information, symbol information, RTTI, etc. Also, we assume that source code of such binaries are not available. Since our VTable extraction and construction call order are based on the ABI specification, we only target binaries compiled with standard C++ compilers, e.g., Clang, GCC and MSVC.

C. Our approach

As a preliminary step, we recover all the VTables in the binary and group them into complete-object VTables. We utilize an already known scanning-based algorithm [19] to extract VTables. These VTables include primary and secondary VTables, which are then grouped to form complete-object VTables. In a nutshell, we start with a primary VTable (i.e., $offsetToTop == 0$), and group it with succeeding secondary VTables (i.e., $offsetToTop \neq 0$) until we reach the next primary VTable. Each unique group is a complete-object VTable and provides a one-to-one mapping between the complete-object VTable and the polymorphic classes in the binary. In the remainder of this section, we outline the analyses we undertake to infer inheritance relationships between the complete-object VTables, i.e., polymorphic classes.

Key insight: Code features that require runtime decisions (e.g., virtual function dispatch) can not be optimized away (i.e., eliminated) by the compiler, and therefore provide a robust source for inheritance inference. Our inheritance inference approach is based on identifying key inference points that *can not* be optimized away during compilation (an exception being removal of entire classes). Particularly, we leverage the virtual functions including virtual destructors to infer inheritance semantics. This way, we ensure meaningful inference even under strong compiler optimization.

a) Combining constructors with destructors: We combine constructor-destructor analysis to achieve optimal recovery. State-of-the-art binary-level class inheritance extraction tools have primarily focused on constructor analysis. However, the number of constructors present in the binary decreases as the level of optimization increases, thus leading to inaccurate inference. Like constructors, destructors also provide insight into a particular class inheritance. Typically, the number of destructors in the binary tend to be larger than the number of constructors (see Table IX in Appendix C).

In order to prevent memory leak, destructors are declared virtual which ensures that specific objects are destructed as expected.

Unlike constructors that can not be virtual, destructors are commonly virtual and therefore, destruction calls are not inlined during optimization.

Because virtual functions are not inlined by compilers, explicit destructors are preserved in memory. This eliminates the possibility of a virtual destructor not being present in the binary. If we can also use destructors for our analysis, then we will be able to address challenge **C1**, since we are no longer completely reliant on constructors–which could be inlined. We could also address **C3**, since we can augment destructors with available constructors.

b) Identifying valid constructors and destructors: Inlining of constructors within other 'host' functions results in false inference of the host function as a constructor. This is one of the main reason for falses in analyzing optimized code. In fact, vptrs initialized in one or more host functions that are neither constructors nor destructors will result in likely false relationship inference between such functions. Therefore, if we can correctly eliminate such functions, we can safely analyze constructors and destructors, and correctly identify explicit calls to (or inlined) base constructors and destructors and also correctly eliminate calls to composed class constructors and destructors. This handles challenge **C2**. Only the constructors assign vptr to the implicit *this* pointer. We employ static analysis to detect whether the *this* pointer is initialized with a vptr. If so, it is classified as a constructor, if not it is a host function that contains inlined constructor.

We also perform additional analysis, explained in Section IV-B to differentiate constructors from destructors. This helps us to address "false constructor identification" under **C1**. In order to address "missed base class constructor calls" for constructors which inline their base constructors, we ensure that the correct primary vptr associated to a constructor is identified. We do the same for destructors with inlined base destructors.

c) Object Layout Analysis (OLA): There are cases where destructors are not virtual, in that case, they could also be inlined just like constructors. This creates the possibility of some classes having neither constructor nor destructor present in the binary. In cases where we can not find an explicit constructor or destructor for a class, we employ intra-procedural static analysis to model the object layout. Specifically, we start from the explicit virtual functions in a class' VTable (note that these functions can not be optimized out). Next, we identify type-revealing instructions within the functions. Starting from these instructions, we obtain a backward slice and back-propagate type information to obtain a mapping:

this + offset ->type

By extending the analysis across all the classes, and checking different class objects for type congruence (i.e., member types at a given offset across all polymorphic classes must be the same), we can eliminate inconsistent inferences.

We further our analysis by using information regarding pure virtual functions in the class VTables to improve recovery. Specifically, if VTable for class A contains a pure virtual function at offset off_1, and VTable for class B does not contain a pure virtual function at offset off_1, then A can not inherit from B.

d) Identifying Completion of main Object Initialization (COI): Completion of initialization of a class' main object (a.k.a main object initalization) is the point during construction where base class vptrs and class' vptrs have all been completely written and overwritten in the object. Construction of composed objects always take place *after* construction of main object has completed. Irrespective of compiler optimization, we can conclude that vptr initializations that occur before this point belong to base classes while those that occur after it belong to composed objects. We found overwrite analysis [18] to be effective in identifying COI. This saves us from relying on explicit base class constructor calls and also helps us to correctly eliminate composed objects from our inheritance. In a case where a standalone constructor does not exist for a class, we depend only on the destructor. For classes with neither constructors nor destructors, we rely on the inference from OLA.

In addition, completion of main object initialization makes it possible to correctly differentiate constructors and destructors from other functions which contain vptr initialization as a result of inlining. This subsequently helps to avoid false positive inheritance inference thereby solving challenge **C1**.

Complexity of the problem: `DeClassifier` attempts to solve a hard problem, directional class hierarchy recovery from optimized binaries. For this reason, we employ standard tools like BAP to lift binary to an intermediate representation. Currently, BAP is unable to analyze large binaries. Therefore, in the current form of `DeClassifier` it inherits this limitation of BAP, however, if BAP is replaced with a more effective static analysis tool, we expect significant improvement in recovery. Also, DeClassifier assigns direction of inheritance when neither constructor nor destructor is available using Object Layout Analysis(OLA), however, if there is not enough information in the binary for OLA, no inheritance will be assigned for the classes involved.

IV. DECLASSIFIER

We have developed `DeClassifier` a class inheritance inference engine that employs static analysis for reconstruction of class hierarchy from optimized C++ binaries. Figure 2 presents the overview of `DeClassifier`.

A. VTable Extraction and Grouping

Complete object VTables are made up of all the VTables that belong to a class. They provide an unlabeled unique representation for each polymorphic class in a given binary. Like other solutions which recover class hierarchy from binaries [6], [18], we treat complete object VTables as analogous to polymorphic classes and they form nodes in the CHT of a program generated by DeClassifier.

Much work has been done on extracting VTables from the binary [9], [19], [28]. Vptrs are scattered throughout the text region of the binary as immediate values. Typically, they

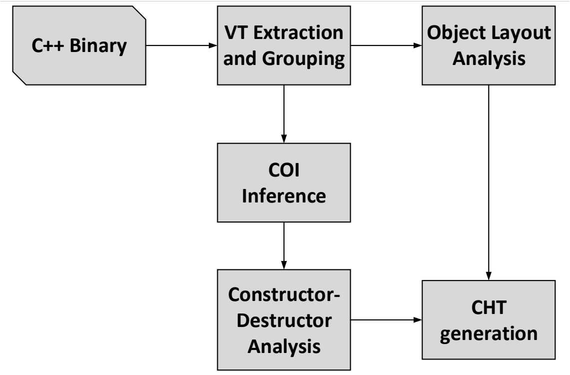


Fig. 2: An overview of DeClassifier

get written into locations in an object by constructors and destructors during object initialization. So we scan the text section to recover all immediate values which point to read-only sections of memory, since VTables are stored in the read-only section to prevent VTable injection attacks. The well defined nature of VTables, particularly the existence of mandatory fields [1] provides us with a signature to filter out recovered immediate values which point to read-only section but are not VTables, for instance, jump tables.

The recovered list of VTables contain all primary and secondary VTables where one or more of them make the complete object VTables for a single polymorphic class. Therefore, from the current list of VTables, we need to construct another list which comprises of only complete object VTables. To achieve this we merge primary VTables with their corresponding set of secondary VTables, with each item being represented by the primary VTable address.

All VTables belonging to a class are laid out contiguously starting from the primary VTable which has an offset-to-top of 0. All the secondary VTables have a non-zero offset-to-top. Given a set of VTables, we first sort them in increasing order of addresses. Then, we merge a primary VTable with all secondary VTables immediately following it. At the end of this process we have a set of complete object VTables.

B. Correct identification of Constructors and Destructors

Correctly differentiating constructors and destructors from other functions with inlined vptr initialization is crucial to eliminating all false positives. Constructor and destructor calls within actual constructors and destructors are those that guarantee inheritance. Functions containing inlined vptr initialization can contain multiple such initializations for different unrelated classes, therefore using any information within them will result in imprecise class hierarchy.

Constructors and destructors initialize the vptrs of the classes they belong to, among other operations they perform. The primary vptr of the class must be eventually written into the first entry of the object, before or after vptr of base classes are written, depending on whether a destructor or constructor is being considered. To do this, the object address gets passed to it, usually as the first argument. Therefore, we scan functions for primary vptr write to zero offset from the object address. We lift the binary to BAP IR and construct use-def chains for each IR variable. Next, we recursively propagate the defines into uses until all IR instructions are a combination of defines corresponding to function inputs. At this point, if the IR instruction corresponding to vptr initialization writes to the memory location pointed to by the first argument (implicit this pointer), we infer the function to be a constructor or a destructor. The instruction that writes vptr is the point of completion of object construction.

Our analysis will correctly distinguish constructors and destructors from functions which inline a constructor or destructor since the object address must be adjusted in order to write the primary vptr in the case of the latter. This gives us the complete set of constructors and destructors. However, we are still left with the task of correctly differentiating between constructors and destructors so that we do not wrongly infer the derived class as the base or vice versa or include composed classes in the inheritance. As discussed in Section II-B, the ordering of initialization of base and derived class vptrs are in the reverse order for constructors and destructors. We infer a function to be a destructor if one of the following is true:

1) Destructors are mostly virtual, so they have entries in the VTables. We check if the function address exists in a VTable.
2) Due to the use of destructors, for destructing objects, they call the delete operator. We also check if the function being verified calls the delete operator. A constructor will not call the delete operator.
3) In cases where explicit calls are made to base class constructor, we check if the calls are made before vptrs are initialized.

All identified constructors and destructors are associated with the primary vptr they belong to. In case of the constructor, it is associated with the last primary vptr written to an object address. This is because if base class constructors are inlined, their vptrs are written first. For destructors, the destructor is associated with the first primary vptr written to the object address. Once we have the complete set of constructors and destructors, we move on to perform constructor-destructor analysis.

C. Constructor-Destructor Analysis

The constructor of a derived class calls the constructors of its base classes (or initializes the base classes' vptrs) before initializing its own vptr(s). Since we have already identified valid constructors in the previous step, we extract all calls to valid constructors that take place before the last write of primary vptr to zero offset of the object being constructed. For inlined base class constructors as in the running example, we extract all complete object VTables (primary and secondary vptrs) initialized also before the last write of primary vptr. Composed classes get initialized, either through explicit constructor call or inlined vptr initialization, only after the complete object VTable of the current class has been initialized. Therefore, we are able to correctly exclude composed classes from our class hierarchy.

In a destructor, the derived class' complete object VTable is first initialized, followed by calls to composed class destructors (or composed class vptr initialization) and finally, calls to base classes destructors. For a destructor, the last primary vptr write to zero offset of the object does not demarcate between base and composed objects destruction. However, the number of secondary vptrs initialized gives us insight into where calls to destructors of base classes begin. The number of VTables (primary and secondary) a class has is equal to the total number of direct base classes it has. To correctly eliminate composed class destructors, we map each vptr initialized to each destructor call starting from the last call(this is because base class destructors are called last). Finally, we ignore other calls which do not have a corresponding vptr initialization. They are the composed class destructor calls which are in between the derived class vptr initialization and base class destructor calls.

For all base class constructor/destructor calls identified, we locate their associated complete object VTable and map them as the bases. In the case of inlined base class constructor/destructor, we directly map the inlined complete object VTable as the base. For the sake of space, we have included the algorithms used to analyze constructors and destructors in Appendix A

D. Object Layout Analysis

We perform object layout analysis on virtual member functions of a class. Particularly, we are interested in member functions that operate on the *this* pointer. Virtual calls to these functions are explicit and can not be inlined, as such, they are available in the binary.

Specifically, we perform coarse type inferencing and label the object with its member types. First, we convert the binary to BAP IR to perform static analysis. Next, we identify type-revealing instructions in the function (`jmp *ebx, mov rdi, rax; call printf,` etc.) and their corresponding IRs. We employ intra-procedural static analysis to identify the offsets within *this* pointer that the types map to. This approach is similar to the type inferencing performed by past efforts such as REWARDS [16]. As an end result, we obtain a type map for offsets within *this* pointer. In order for an inheritance relationship between two classes to be correct, types of member variables in the two classes at specific offsets must be congruent (compatible) to each other.

Next, we use overwrite analysis. For construction, base class vptrs are written followed by those of the derived class and the reverse is done for destruction. However, since there is no way to infer if an inlined vptr initialization belongs to a constructor or destructor, the order of overwrite cannot be used to infer direction of inheritance. Therefore, we use the result of OLA to decide direction of inheritance for relationships identified through overwrite analysis. We analyze specific attributes of an object as well as its complete object VTable. We consider presence of pure virtual functions, type congruence and VTable size.

a) Pure Virtual Function: We perform pure virtual functions validation to further filter inaccuracies in inheritance inference. The presence or number of pure virtual functions in two VTables provides unidirectionality of inheritance since the VTable without pure virtual functions has to have derived from the VTable with pure virtual functions. We considered these two possible cases:

1) One VTable has pure virtual function entries while the other has none
2) One VTable has more virtual function entries than the other, with both having those entries at the same offsets.

b) Minimum Object Size Analysis: Analyzing the size of an object can be done either dynamically or statically. The dynamic analysis approach has two major challenges, 1) coverage and 2) how to compute size of stack and global objects. Objects are created in three major locations at runtime, heap, stack and global region of the memory. To create objects on the heap, the new operator must be called which can be hooked to get the size passed to malloc (that will be upper bound for the object size). However, size of stack objects pose a challenge in the sense that there is no difference between the stack pointer movement when memory is allocated for a local variable (e.g an integer variable) and for an object.

In this work, we analyze object size statically to obtain a lower bound object size. With this approach, coverage is not a challenge and neither is the location of an object a challenge. Just like constructors and destructors, the first argument passed to member function of a class is the object address. To access a member variable, a literal value is added to the object address (i.e. *this* pointer) to reach that variable. The maximum offset that can be added to the *this* pointer will always be less than the size of the object itself, which gives a lower bound for the object size. Identifying non virtual functions of a class is challenging, however, pointers to all virtual functions of a class reside in the complete object VTable for that class. For every complete object VTable identified, we analyze each virtual function it contains to obtain the maximum offset accessed from the *this* pointer. We associate this value to the complete object VTable as the lower bound for its object size.

c) VTable Offset to top: Considering the case of multiple inheritance, the derived object consists of sub-objects of its base classes. Offset-to-top refers to the offset of a given base-in-derived object from the top of the derived object. The offset-top-top value for each base class is stored in the offset-to-top field of the vtable corresponding to that base class. As already mentioned, one of the operations performed within a constructor is calling the constructor of base classes. Before this call is made, the constructor adds the offset-to-top value for the given base class to the *thisptr* in order to reach the base class sub-object. Hence, we compare the offset-to-top value with the offset at the constructor call site for equality to conclude on inheritance between the two classes.

d) VTable Size: We compute the VTable size of a class as the total number of virtual functions pointer, pure virtual functions and zero destructor entries (this exists only in the VTables of abstract classes) that it contain. We do not consider the complete object VTable in this case because, relationships can be identified between a secondary VTable and a primary VTable. Therefore we ensure that only the associated VTable sizes are considered.

VTable sizes increase or remain steady down a particular inheritance chain, the VTable size of a derived class is always greater than or equal to that of its base class. Hence, the sizes of two VTables found to be related provide indication of direction of inheritance.

E. Performing overwrite analysis

We analyze each function identified to contain inlined constructor or destructor, examining every VTable writes (both primary and secondary) that they perform. VTable pointers written to the same memory locations are grouped together as being related. In Marx, if overwrite analysis identifies two vptrs A and B to be related and also finds B and C to be related, the three vptrs A, B and C are grouped to be in the same set even though A and C might not be related. In this work, once we identify a relationship between A and B, we immediately use the result from OLA to decide the direction of inheritance and then continue building up the class hierarchy with subsequent relationships.

We locate vptr overwrites in two ways, 1. if the object address passed to a known constructor or destructor is the same location where a primary or secondary vptr is written, and 2. if multiple vptrs are written in the same memory location. Note that these overwrites are considered on a function by function basis. For the first case, we locate the primary vptr associated with the constructor or destruction that is being called.

Object sizes are associated with the primary vptr of a complete object VTable. With multiple inheritance, a secondary vptr will overwrite a primary VTable or vice verse. Therefore, we also locate the corresponding primary VTable of every secondary VTable in any identified group of related vptrs. We are able to locate corresponding primary VTable with VTable grouping explained in Section IV-A.

F. CHT Generation

In this phase, we build the complete Class Hierarchy Tree for the binary being analyzed by combining the relationships identified during constructor-destructor analysis phase with those identified by overwrite analysis. Constructor-destructor analysis directly assigns direction to any relationship it recovers using the order of calls or vptr initialization. For relationships recovered through overwrite analysis, we use attributes obtained from OLA to assign direction of inheritance.

We apply the following rules to infer inheritance:

- If constructor of class A calls constructor B before completion of object construction, A inherits from B. Converse holds true for destructors.
- Class A inherits from Class B only if size of object A $\geq$ size of object B.
- Class A inherits from Class B only if size of VTable of class A $\geq$ size of VTable of class B.
- Class A inherits from Class B only if type of each member in B given by $this_B + offset$ (from OLA) is compatible with the type of corresponding member $this_A + offset$ in A.
- Class A inherits from Class B only if for each pure virtual function in VTable of A, the corresponding virtual function in VTable of B is also pure virtual.
- Class C is a secondary base of class A only if the `offsetToTop` value in secondary VTable of A is equal to the displacement that must be added to an object of A to reach the C sub-object in A (obtained through OLA). For example, in the running example, the C sub-object in D can be obtained by adding 16 to the base address of D, which is nothing but the `offsetToTop` value (-16) in secondary VTable of D.

Once all decisions about direction of inheritance is made, we combine all edges to build the CHT of the binary.

V. EVALUATION

Our evaluation aims to answer the following questions:

- What fraction of the entire class hierarchy of a program can `DeClassifier` recover?
- How precise is the recovered class hierarchy?
- How effective is our direction of inheritance assignment using OLA?
- How does `DeClassifier` outperform constructor only analysis for recovering class hierarchy.

All binaries were compiled using gcc with O0 and O2 optimization. We do not consider O3 optimization in the main evaluation because in terms of inlining, similar binaries are produced with O2 and O3. However, we have included results for SPEC2006 binaries compiled with O3 optimization in the Appendix (see Appendix D). All analysis experiments were performed on Ubuntu 16.04 LTS running on Intel core i7 3.60GHz with 32GB RAM. We did not evaluate Node and Mongodb because BAP was unable to analyze them. Mongodb is too large for it and there was a runtime error while analyzing Node. We reported this error to BAP team and they acknowledged it is a bug in BAP which would be worked on. All SPEC2006 benchmark programs with polymorphic classes were considered except for Astar and Namd. Astar has just one polymorphic class, there is no edge for comparison. Namd has 3 polymorphic classes, where two of the classes inherit from the third. However, when compiled with O2 optimization, the VTable of the third gets optimized out.

A. Ground Truth

We obtained the ground truth for standalone programs by compiling them with the `-fdump-class-hierarchy` option on GCC. This generates a .class file for each .cpp file with at least one polymorphic class which contains VTables as well as the inheritance of those classes. However, since the 7 WX Widget programs in our test set are together in a single package, there is no way we could distinguish the

TABLE I: CHT recovery results for binaries compiled with gcc -O0. Column with “inh = 0” contains # of classes that do not inherit from any class, “inh = 1” contains # of classes that inherit from exactly 1 immediate base class, and “inh >1” contains # of classes that inherit from more than 1 immediate base classes.

Programs	Ground Truth				Analysis						
	#Classes	inh=0	inh=1	inh>1	#Classes	Ctor only			Ctor+Dtor		
						inh = 0	inh = 1	inh >1	inh = 0	inh = 1	inher >1
libebml	27	5	22	0	26	14	12	0	7	19	0
libflac	18	8	10	0	18	12	6	0	8	10	0
libzmq	76	17	47	12	76	39	29	8	17	47	12
libwx_baseu	285	24	258	3	287	157	128	2	49	235	3
libwx_baseu_net	44	27	15	2	44	35	8	1	27	15	2
libwx_gtk2u_adv	266	150	114	2	266	199	67	0	146	117	3
libwx_gtk2u_aui	62	51	11	0	62	58	4	0	52	9	1
libwx_gtk2_core	683	220	445	18	683	408	263	12	242	419	22
libwx_gtk2u_html	138	66	70	2	138	104	34	0	65	71	2
libwx_gtk2u_xrc	122	110	12	0	122	116	6	0	111	11	0
Doxygen	974	208	670	96	944	462	417	65	222	629	93
Xalanc	975	317	643	15	968	472	486	10	308	646	14
DealII	884	34	846	4	689	431	256	2	47	639	3
Omnetpp	112	10	102	0	109	50	59	0	11	98	0
Soplex	29	8	20	1	29	18	11	0	8	20	1
Povray	32	11	21	0	29	16	13	0	12	17	0

TABLE II: CHT recovery results for binaries compiled with gcc -O2. Column with “inh = 0” contains # of classes that do not inherit from any class, “inh = 1” contains # of classes that inherit from exactly 1 immediate base class, and “inh >1” contains # of classes that inherit from more than 1 immediate base classes.

Programs	#Classes	Ctor only			Ctor+Dtor			Ctor+Dtor + Object Layout Analysis (OLA)		
		inh = 0	inh = 1	inh >1	inh = 0	inh = 1	inher >1	inh = 0	inh = 1	inher >1
libebml	26	14	12	0	7	19	0	7	19	0
libflac	18	15	3	0	8	10	0	8	10	0
libzmq	63	35	24	4	23	37	4	22	40	2
libwx_baseu	262	233	29	0	171	91	0	153	108	1
libwx_baseu_net	43	37	6	0	29	14	0	29	14	0
libwx_gtk2u_adv	229	214	15	0	197	18	0	193	35	1
libwx_gtk2u_aui	59	57	2	0	57	2	0	54	5	0
libwx_gtk2_core	621	566	55	0	486	135	0	364	240	17
libwx_gtk2u_html	123	118	5	0	104	19	0	104	19	0
libwx_gtk2u_xrc	93	93	0	0	93	0	0	93	0	0
Doxygen	870	845	23	0	458	400	12	483	446	5
Xalanc	875	615	258	2	396	479	0	410	457	8
DealII	687	544	140	3	123	561	3	96	579	11
Omnetpp	105	69	36	0	36	69	0	8	91	5
Soplex	25	23	2	0	21	3	1	19	6	0
Povray	24	21	3	0	17	7	0	17	7	0

classes that belong to each of the program using the output of `-fdump-class-hierarchy`. Therefore, we compiled the program with the `-frtti` option with no optimization and then analyzed the RTTI structures in each of the binaries to obtain the ground truth inheritance.

B. Precision and Recall

In order to measure the performance of `DeClassifier` we evaluated precision *P* and Recall *R* of the class hierarchy recovered from each of the 16 binaries considered. Precision answers the question of what fraction of the class hierarchy recovered is correct and what fraction is wrong, while recall answers the question of what fraction of the ground truth class hierarchy has been recovered and what fraction is not recovered (see Appendix B for formulas).

Table I and Table II show the breakdown of classes based on the number of classes they inherit from for O0 and O2 optimization levels respectively. Table III and Table IV show the precision and recall of Ctor only analysis, Ctor+Dtor analysis as well as Ctor+Dtor+OLA for O0 and O2 optmization levels respectively.

Recall for O0 binaries was computed using all found edges in the ground truth. However, this is done differently for O2 binaries. Due to optimization, some classes (VTables) get removed by the compiler and the fact that our tool does not recover such classes does not make it less effective since they are in fact not available in the binary. To ensure these classes do not influence the recall recorded, we identified them and removed edges which have them as either derived or base from the ground truth to compare with. Basically, for O2 binaries, we computed recall by comparing with a subset ground truth which is based on the available classes(VTable) found in the binary. Columns labeled ”GT” and ”Used” under ”#Edges” in Table IV show the number of edges in the overall ground truth and the number of edges remaining after removing edges with

TABLE III: Precision and Recall of CHT generated by `DeClassifier` for O0 Optimization with GCC. Comparison was done with the overall ground truth

Programs	#Classes in GT	#Classes in Binary	Ctor only		Ctor+Dtor	
			Precision(%)	Recall(%)	Precision(%)	Recall(%)
libebml	27	26	100	54.5	100	86.4
libflac	18	18	100	60	100	100
libzmq	76	76	95.7	59.2	97.3	96.1
libwx_baseu	285	287	99.2	49	98.3	89.8
libwx_baseu_net	44	44	100	52.6	100	100
libwx_gtk2u_adv	266	266	94.0	50	91.9	95.8
libwx_gtk2u_aui	62	62	100	44.4	90.9	90.9
libwx_gtk2_core	683	683	98.6	58	97.2	93.8
libwx_gtk2u_html	138	138	100	48.6	98.7	100
libwx_gtk2u_xrc	122	122	100	45.5	100	91.7
Average			**98.8**	**52.2**	**97.4**	**94.5**
Doxygen	974	944	99.8	63.4	98.9	93.5
Xalanc	975	968	100	70.4	100	97.5
DealII	874	689	95	28.9	99.8	75.3
Omnetpp	112	109	100	57.8	100	96.1
Soplex	29	29	100	50	100	100
Povray	32	29	100	61.9	100	81.0
Average			**99.13**	**55.4**	**99.8**	**90.6**

TABLE IV: Precision and Recall of CHT generated by `DeClassifier` for O2 Optimization with GCC. Comparison was done with those edges in ground truth whose corresponding VTables were found in the binary

Program	#Classes		#Edges		Ctor only		Ctor + Dtor		Ctor + Dtor + OLA	
	GT	Binary	GT	Used	Precision(%)	Recall(%)	Precision(%)	Recall(%)	Precision(%)	Recall(%)
libebml	27	26	22	22	100.0	54.6	100.0	86.4	100.0	86.4
libflac	18	18	10	10	100.0	30.0	100.0	100.0	100.0	100.0
libzmq	76	64	76	53	100.0	60.4	97.8	75.5	100.0	79.3
libwx_baseu	285	262	264	198	100.0	14.1	100.0	43.9	100.0	47.5
libwx_baseu_net	44	43	19	17	100.0	35.3	92.9	76.5	100.0	82.4
libwx_gtk2u_adv	266	229	118	83	100.0	18.1	88.2	18.1	91.4	38.6
libwx_gtk2u_aui	62	59	11	11	50.0	11.1	50.0	11.1	80.0	44.4
libwx_gtk2_core	683	621	481	293	95.1	13.3	94.7	30.4	93.8	61.4
libwx_gtk2u_html	138	123	74	36	100.0	13.9	88.9	44.4	89.5	47.2
libwx_gtk2u_xrc	122	102	12	-	0.0	0.0	0.0	0.0	0.0	0.0
Average					**84.5**	**25.1**	**81.3**	**48.6**	**85.4**	**58.4**
Doxygen	974	870	866	469	100.0	3.0	68.2	57.6	94.7	80.2
Xalanc	975	875	710	577	100.0	45.4	78.7	65.3	98.3	79.4
DealII	874	687	854	678	98.4	18.6	99.1	80.1	98.4	81.9
Omnetpp	112	105	102	97	100.0	22.7	100.0	58.8	98.7	78.4
Soplex	29	25	22	12	100.0	8.3	66.7	16.7	100.0	50.0
Povray	32	24	21	12	100.0	23.1	100.0	58.3	100.0	58.3
Average					**99.7**	**20.2**	**85.5**	**56.1**	**98.4**	**71.4**

TABLE V: Number of direction of inheritance "correctly assigned", "wrongly assigned" and not "assigned" by OLA

Programs	Correctly assigned	Wrongly assigned	Not assigned
libebml	19	0	0
libflac	10	0	0
libzmq	42	0	2
libwx_baseu	94	0	0
libwx_baseu_net	14	0	0
libwx_gtk2u_adv	32	0	8
libwx_gtk2u_aui	4	0	0
libwx_gtk2_core	171	2	20
libwx_gtk2u_html	17	0	1
Doxygen	373	2	49
Xalanc	459	0	17
DealII	555	11	10
Omnetpp	73	4	0
Soplex	6	0	1
Povray	7	2	0

classes not found in the binary.

The average precision and recall of class hierarchy recovered by `DeClassifier` on O0 binaries are 97.4% and 94.5% for libraries and 99.8% and 90.6% for executables respectively. And on O2 binaries, it has an average precision and recall of 85.4% and 58.4% for libraries and 98.4% and 71.4% for executables respectively. `DeClassifier` was unable to recover any hierarchy for libwx_gtk2u_xrc.

C. *Effectiveness of Direction Assignment using OLA*

In this subsection, we discuss the effectiveness of direction of inheritance assignment using OLA. As discussed in section IV-F, after identifying a relationship between two classes using overwrite analysis, we use OLA to assign the direction of inheritance. Table V shows the number of directions correctly assigned, the number wrongly assigned (i.e. assigning the derived as the base) and the number not assigned at all. We do not assign direction of inheritance between two classes whenever there is no enough information from OLA about those classes. On the average, directions of inheritance were correctly assigned to 93.6% of relationships identified, 1% were wrongly assigned and 5.4% were not assigned at all.

D. *Comparison with Constructor only Analysis*

Table III and Table IV show how recall significantly increases from Ctor only analysis, to Ctor-Dtor + OLA. Precision decreases slightly from Ctor only to Ctor-Dtor, but increases again for Ctor-Dtor + OLA analysis. Such decrease in precision is recorded because, for destructor analysis, vptrs are mapped to base class destructors starting from the last call.

As a result, if a class has no base class, but has a template class, the template class will be wrongly identified as its base class. However, with overwrite analysis, we are able to see that no overwrite actually happens between the two vptrs involved. First, the combination of destructor and constructor significantly increased the recovery compared to using constructors alone. Secondly, combining these with OLA helped to recover all other details in the binary that are unavailable from either constructor or destructor analysis as a result of optimization. For O0 binaries, the average recall increased from 52.2% to 94.5% for libraries and from 55.4% to 90.6% for executables for Ctor only and Ctor-Dtor analysis respectively. Since no optimization is performed on O0 binaries, overwrite analysis improved neither precision nor recall, for this reason, we did not include a different column for overwrite analysis. For O2 binaries, the tables show that recall increased from 25.1% to 48.6% to 58.4% for libraries and from 20.2% to 56.1% to 71.4% for executables for Ctor only, Ctor-Dtor and Ctor-Dtor + OLA respectively.

E. Comparing `DeClassifier` *with other Class Hierarchy Recovery Solutions*

Table VI summarizes existing class hierarchy recovery solutions based on capabilities and techniques. We considered the following:

1) HandleInlining: Can correctly identify relationships when constructors or destructors are inlined either in derived class constructors or destructors or in other functions.
2) InhVsComp: Can differentiate inheritance from composition.
3) DtorAnalysis: Uses destructor analysis.
4) CHTRecovery: The format in which inheritance tree is recovered. The edges can either be directed or undirected. All related classes can also be grouped together or not.

We ran Marx on some binaries. We found out that it can handle 1 and 2 however, the class hierarchy recovered are grouped into sub trees. The approach proposed by Katz et al [13] is similar to Marx based on the features we consider here. We contacted the authors of VCI for the source code but they did not release it to us. From the description in the literatures for VCI, SmartDec and Hex Rays, we see that they canot handle 1 and they can handle 2 only when there is no optimization. Also, they do not consider 3 and all hierarchy recovered are directed. ObjDigger does not handle any of the capabilities we considered. Lego handles inlined constructors, but does not handle 2 and does not consider 3. CHT are directed.

VI. DISCUSSION

A. Falses—Root Cause Analysis

a) Inaccuracies in static disassembly: We did not expect to find any false relationship from overwrite analysis, however, this is as a result of inaccuracies in static disassembly. In the disassembly produced by BAP for the snippet below, the sequence of instructions after 4 is 6, 7, 5. But there is no actual branch instruction to go back to 5 if the jump is executed. At 7, the content of rbx is stored back in rdi, which is the same location where 0xEDFDA8 is stored at 2. As a result, the rdi value passed to the destructor of InheritedMemberInfoContext::Private is the same as the location where 0xEDFDA8 is written. Therefore our overwrite analysis identifies 0xEDFDA8 and the primary vptr of InheritedMemberInfoContext::Private as being related whereas they are not. If this were dynamic analysis, instruction 5 will not be executed if the jump is executed.

TABLE VI: Solutions that extract <u>at least partial</u> Class Hierarchy Tree (CHT) from C++ binaries, their key techniques and limitations. Entry p implies recovery only when ctors not inlined.

Solution	**Key Technique**	**Handle-Inlining**	**InhVs-Comp**	**Dtor-Analysis**	**CHT-Recovery**
VCI [6]	Static ctor analysis	✗	p	✗	Directed
Marx [18]	Static overwrite analysis	✓	✓	✗	Undirected Sub-Tree Grouping
Katz et al. [13]	Object tracelet, predictive modeling	✓	✓	✗	Undirected Sub-Tree Grouping
SmartDec [7], [8]	Static ctor analysis	✗	p	✗	Directed
ObjDigger [12]	Symbolic execution, data flow analysis	✗	✗	✗	Not applicable
Lego [24]	Dynamic overwrite analysis	✓	✗	✗	Directed
Hex Rays [23]	Static ctor analysis	✗	p	✗	Directed
DeClassifier	Static ctor-dtor, overwrite analysis	✓	✓	✓	Directed

```
1 mov rbx, rdi ...
2 mov qword ptr [rdi], offset off_EDFDA8 ...
3 mov rdi, rpb
4 jnz short loc_6
5 call InheritedMemberInfoContext::Private::~Private() ...
6 ...
7 mov rdi, rbx ...
```

b) Missing VTables: With higher levels of optimization, the compiler removes the entire VTable of any class whose instance is not created irrespective of whether an instance of its base class is created. In Table VII, we counted the total number of classes which constitute the edges not recovered by `DeClassifier` for both libraries and executables. Constructor-destructor as well as a OLA ensure that every information present in the binary is recovered, however, if information is not present in the binary, there is nothing to work with.

c) Optimized vptr Initialization: We found two cases of optimized vptr initialization that the compiler performs. These initializations violate the typical construction/destruction behavior assumed by prior efforts.

a. Missing intermediate class initialization: The below code snippet shows the destructor of class SList<MemberList>in doxygen.

```
Slist<MemberList>::~Slist() ...
mov rbx, rdi
#Init vptr of Slist<MemberList>
mov [rdi], 0xb49d90 ...
mov rdi, rbx ...
#Call dtor of most base class
```

TABLE VII: Column 2 shows the total number of classes that make up the missing edges for O2 optimization, column 3 shows the number of those classes whose VTables were not found in the binary

Programs	#Polymorphic Classes missing edges (**Col A**)	#Classes in **Col A** without VTables in Bin
libzmq	20	13
libwx_baseu	88	27
libwx_baseu_net	6	3
libwx_gtk2u_adv	63	22
libwx_gtk2u_aui	5	5
libwx_gtk2u_core	198	68
libwx_gtk2u_html	13	7
Doxygen	178	100
Xalanc	158	84
Omnetpp	13	5
DealII	257	169
Soplex	3	2
Povray	16	4

```
call QGList::~QGList() ...
```

From the ground truth, the direct base class of SList<MemberList>is QList<MemberList>, which inherits from QGList. However, the snippet shows that call to the destructor of QList<MemberList>has been optimized and replaced with that of the most base class. In cases like this, we are unable to identify the direct base class. Table VIII shows the number of edges with missing intermediate base class. Note that for our evaluation, we neither consider this edges as false positives nor true positives.

b. Missing all bases: The below code snippet shows the only instance of construction of class SPxHarrisRT in Soplex which inherits from SPxRatioTester.

```
int _cdecl main(): ...
call operator new(unsigned long) ...
#Init vptr of soplex::SPxHarrisRT
mov [rax], 0x457b50
```

However in the binary, only the vptr of SPxHarrisRT gets written into the object address, without initialization of the vptr of SPxRatioTester. Other derived classes of SPxRatioTester were initialized similarly. We found such cases to be common, and leads to inference inaccuracy.

VII. RELATED WORK

Multiple prior C++ binary-level solutions have recovered semantic information from a binary [5], [6], [9], [18], [19], [26], [28]. However, VCI [6] and Marx [18] are the most recent and relevant tools closest to our work. VCI uses constructor only analysis to reconstruct the class inheritance of a program. They handle constructor inlining by relaxing the requirement that the vptr is written into the first argument (implicit this pointer) passed to the function being analyzed. This results in wrong identification of functions as constructors which subsequently result in false inheritance inference.

Andre et al. [18] presented Marx which reconstructs class inheritance from binary using certain heuristics. It uses overwrite analysis and groups vptrs written into the same memory location into a single set, only related vptrs get overwritten in the same memory location. Even though Marx is able to correctly group related classes into sets, it does not reason about the direction of inheritance which significantly limits its application.

OBJDigger, presented by Jin et al. [12], uses symbolic execution and inter-procedural data flow analysis to recover object instances, data members and methods of the same class. This is achieved by tracking the usage and propagation of the *this pointer* within and between functions. While the authors did not attempt to recover class inheritance, a method to achieve that was described. However, this can only identify primary base class since they assume that a base class will write its vptr only in the zero offset from the object address. A secondary base class will write to a positive non-zero offset from the object address but that was not accounted for.

Fokin et al. [8] presented SmartDec which partially recovers certain C++ specific language constructs statically. It attempts to recover classes and their inheritance, virtual and non-virtual member functions, calls to virtual functions, exception raising and handling statements. Its main limitation is the inability to differentiate between between inheritance and composition which results in wrong relationship inference.

Rewards [16] is one of many (e.g., TIE [15], Laika [4]) data structure reverse engineering tools to infer type information from binaries. It uses dynamic analysis to recover syntax and semantics of data structures observed during execution. Rewards only attempts to infer primitive data types of variables and their semantics.

OOAnalyzer [22] mainly groups methods into classes by combining traditional binary analysis, symbolic analysis and Prolog-based reasoning. The paper explained that class size and VTable size can be considered to decide inheritance. Since OOAnalyzer also considers non-polymorphic classes, one would assume that class size will be relied upon more for this. However, this was not evaluated, therefore, there is no way to confirm the claim that OOAnalyzer can decide inheritance.

VIII. CONCLUSION

Extracting class inheritance tree from optimized C++ code is hard, yet useful. We present `DeClassifier`, a static-analysis based inference engine that employs multiple novel techniques and infers significant amount of directed class inheritance tree from 15 C++ binaries compiled with gcc O0 and O2 options.

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TABLE VIII: Number of false positives recovered by Ctor only analysis, Ctor-Dtor analysis and Ctor-Dtor + OLA analysis for O2 binaries. "Total edges not found" refers to edges in `DeClassifier`'s output but not in ground truth. "MIB" refers to Missing Immediate Base. "Actual false positive" refers to actual false positive edges recovered by `DeClassifier`

Programs	Ctor only			Ctor + Dtor			Ctor + Dtor + OLA		
	Total edges not found	Edges from MIB	Actual False +ve	Total edges not found	Edges from MIB	Actual False +ve	Total edges not found	Edges from MIB	Actual False +ve
libebml	0	0	0	0	0	0	0	0	0
libflac	0	0	0	0	0	0	0	0	0
libzmq	0	0	0	1	0	1	0	0	0
libwx_baseu	1	1	0	4	4	0	15	15	0
libwx_baseu_net	0	0	0	1	0	1	0	0	0
libwx_gtk2u_adv	0	0	0	3	1	2	4	1	3
libwx_gtk2u_aui	1	0	1	1	0	1	1	0	1
libwx_gtk2_core	16	14	2	48	43	5	90	76	14
libwx_gtk2u_html	0	0	0	3	1	2	2	0	2
libwx_gtk2u_xrc	0	0	0	0	0	0	0	0	0
Doxygen	9	9	0	142	16	126	77	53	24
Xalanc	0	0	0	102	0	102	6	1	5
DealII	20	18	2	24	19	5	52	32	20
Omnetpp	14	14	0	12	12	0	24	21	3
Soplex	1	1	0	3	2	1	0	0	0
Povray	0	0	0	0	0	0	0	0	0

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APPENDIX

A. Algorithms for Constructor-Destructor Analysis

Below are the algorithms used for constructor-destructor analysis

Algorithm 1 CtorAnalysis analyzes constructors in $\mathcal{C}$ to identify the base classes of a class whose constructor is being analyzed.

```
procedure CtorAnalysis($\mathcal{C}$)
    for each $c$ in $\mathcal{C}$ do
        $ownerPryVT \leftarrow getPrimaryVT(c)$
        $coi \leftarrow getCOI(c)$
        for each $instr$ in $c$ do
            if $isCall(instr) \&\& addressOf(instr) <= coi$ then
                $target \leftarrow getTarget(instr)$
                if $target in \mathcal{C}$ then
                    $basePryVT \leftarrow getPrimaryVT(target)$
                    $Base\{ownerPryVT\}.append(basePryVT)$
                end if
            end if
        end for
    end for
    return $Base$
end procedure
```

Algorithm 2 DtorAnalysis analyzes destructors in $\mathcal{D}$ to identify the base classes of a class whose destructor is being analyzed.

```
procedure DtorAnalysis($\mathcal{D}$)
    for each $d$ in $\mathcal{D}$ do
        $ownerPryVT \leftarrow getPrimaryVT(d)$
        $coi \leftarrow getCOI(d)$
        $noVTs \leftarrow getNoOfVTs(d)$
        for each $instr$ in $d$ do
            if $isCall(instr) \&\& addressOf(instr) <= coi$ then
                $target \leftarrow getTarget(instr)$
                if $target in \mathcal{D}$ then
                    $allCalls.append(basePryVT)$
                end if
            end if
        end for
        for $i = lenghtOf(allCalls) - 1\ to\ 0$ do
            $basePryVT \leftarrow getPrimaryVT(allCalls[i])$
            $Base_{ownerPryVT}.append(basePryVT)$
            $no_VTs = no_VTs - getNoOfVTs(allCalls[i])$
            if $!(noVTs > 0)$ then
                break
            end if
        end for
    end for
    return $Base$
end procedure
```

B. Formulas for Precision and Recall

Precision is defined as follows:

$$P = \frac{TP}{TP + FP} \tag{1}$$

Recall is defined as follows:

$$R = \frac{TP}{TP + FN} \tag{2}$$

where *TP*, *FP* and *FN* refer to the number of derived-to-base edges recovered which match edges in the ground truth, number of edges which do not match any in the ground truth and number of edges in the ground truth not recovered.

C. Effect of Optimization on function inlining

Results of the number of constructors and destructors remaining in the binary when compiled with O0 and O2 optimizations.

TABLE IX: Table showing the number of constructors and destructors present in O0 and O2 binaries. It also shows functions with inlined constructors which other solutions could wrongly identify as constructors.

Programs	O0			O2		
	Ctor	Dtor	Fns with inlined ctor/dtor	Ctor	Dtor	Fns with inlined ctor/dtor
Mongodb	3544	2063	40	725	1046	2638
Node	2930	2546	75	290	447	2520
Doxygen	1010	940	16	245	751	744
Soplex	29	25	4	10	12	3
Povray	47	24	9	40	19	20
Namd	4	4	0	0	1	2
Omnetpp	175	108	3	113	98	104
DealII	582	702	48	390	677	497
Xalanc	1391	958	309	954	771	1989
libebml	41	18	26	42	18	25
libflac++	45	18	0	29	18	5
libzmq	82	76	0	58	38	11
libwx_baseu_net	47	44	2	22	35	33
libwx_baseu	371	287	0	158	257	209
libwx_gtk2u_adv	310	259	12	48	155	240
libwx_gtk2u_aui	74	59	0	18	46	55
libwx_gtk2u_core	929	679	3	357	428	857
libwx_gtk2u_html	140	136	0	26	66	91
libwx_gtk2u_xrc	120	116	2	71	12	41

D. Results for SPEC 2006 binaries compiled with O3 optimization

The average precision and recall of class hierarchy recovered by `DeClassifier` for SPEC2006 benchmark programs compiled with O3 optimization are 91.27% and 67.02% respectively

TABLE X: Precision and Recall of CHT generated by `DeClassifier` for O3 Optimization with GCC. Comparison was done with those edges in ground truth whose corresponding VTables were found in the binary

Programs	#Classes		#Edges		Ctor + Dtor + OLA				
	GT	Binary	GT	Used	inh = 0	inh = 1	inh >1	precision	recall
Soplex	29	25	22	8	19	5	1	83.3	62.5
Povray	32	26	21	12	18	7	0	85.7	50.0
Omnetpp	112	105	102	97	8	96	1	98.4	63.9
Xalanc	975	876	710	570	410	449	13	93.5	77.9
DealII	874	722	854	652	117	572	12	95.5	80.8
Average								91.3	67.0