

# Type Flattening Obfuscation

Ta Thanh Dinh

tathanhdinh@gmail.com

**Abstract**—Beside data and control flow, high-level types are important in binary code analysis, particularly in decompilation. Some research papers have introduced methods to map machine-dependent objects into types of some C-like type system. For the obfuscation/anti-decompilation purpose, we present a technique which bypasses existing type recovery approaches. We have implemented a prototype obfuscating C compiler to demonstrate the technique, the compiler is given open source.

**Index Terms**—type recovery, decompilation, obfuscation

## 1. Introduction

Binary code *decompilation* [4] is to transform the low-level, machine-dependent code of a program into a high-level form, like code of a high-level language. In almost all academic research papers and commercial products, the target language is C. Similar to compilers, a modern binary code decompiler consists of many phases [4, 9]: disassembly, function boundary detection, immediate representation (IR) lifting, control-flow graph (CFG) recovery, high-level variables detection, type (i.e. variable types and function signatures) recovery, etc. Each phase requires particular but not independent [6] analysis techniques: the results of one can affect another. The analyzed program is transformed gradually into a higher-level, more abstract and more understandable representation.

In the opposite direction, binary code *obfuscation* is a method to protect the low-level code from being decompiled, or from being analyzed in general. Because the code analysis contains of different interdependent phases, the obfuscation [11, 22] can proceed at any of them, e.g. anti-disassembly (binary packer, self-modifying code), binary stripping, control-flow flattening, virtualization (for both data and control obfuscation)... just name a few. Basically, each obfuscation method consists of one or several *semantics-preserving* transformations [7, 11] which hide certain properties of the code.

An optional feature of binary code decompilation is *type reconstruction*, namely to recover high-level types from machine-dependent objects [5, 9]. This is the research objective of some research papers [13, 15, 18, 19], and killing feature of commercial [27, 28] as well as open source [26] binary code analysis tools. Beside decompilation, types and particularly *function signatures* are also essential in numerous applications, e.g. static binary rewriting [12, 14] and raising [24], see for example [16] for a more completed list. Thus the knowledge about types expand the attack surface since more analysis can be applied on the programs.

Despite of successes in binary type reconstruction and the need of protecting function signatures, to the best

of our knowledge there is no explicit effort in hiding type information. This paper presents a method for type obfuscation, the principal idea is based on the fact that the compiler does not need to preserve all information about high-level types (type erasure), then with specific tricks we can exploit the *semantics gap* between the high-level language and machine code to make some information very hard if not impossible to be recovered. We do not claim that all type information can be hidden, the attacker can eventually know some but it would be hard to distinguish the concrete underlying types from one to another, thus the proposed notion of *type flattening*.

We implement the tricks in *uCc*, an open source obfuscating C compiler which obfuscates function signatures. The functions in binaries generated by *uCc* can be perfectly analyzed by classical procedures (boundary detection, disassembling, CFG recovery, etc), only their signatures are obfuscated. That way, we can evaluate the effectiveness of type obfuscation tricks on function signatures while excluding unwanted obfuscation effects that may come from (bad) results of other analysis phases. We find that Mixed Boolean Arithmetic (MBA) expressions [10, 21] are a good match for the goal.

In summary, our contributions are as follows:

- We introduce the notion of *type flattening*, it aims at protecting a high-level property (types) of the program in contrast with classical methods which focus on lower properties as data or control flow.
- We build a prototype compiler *uCc* to realize the ideas of type flattening obfuscation. *uCc* also implements the permutation polynomials of MBA [10] while other open source state-of-the-art obfuscators (e.g. Tigress [29]) give only basic arithmetic encoding expressions. Other deobfuscation tools (e.g. Syntia [20], QSynth [25]) can profit *uCc* to test their capabilities of MBA simplification.
- We evaluate the binaries generated by *uCc* against decent decompilers, the results show that no one can detect correctly the underlying types of arguments on function signatures: the original types are indistinguishable from the highest types in the C's integer conversion rank.

## 2. Brief history of binary type inference

In statically typed languages, the compiler does not need preserve source code level type information in the generated machine code (type erasure), then type recovering requires special techniques. A broad survey for research up until 2015 can be referenced in [16], but it sustained a storage point of view bias: types are attached always with

some storage primitives (e.g. registers, memory), there are no essential differences between types and data structures. Actually, types are compile-time constraints, they may or may not have runtime storage imprints. An example is C's *type qualifier* (e.g. `const`, `restrict`), in general any *refinement type* should not leave storage traces, the same thing with generics. Also, the survey lacks some important papers which are only published until later [18, 19].

We review quickly some semantics-based approaches, recent research using machine learning [23] or statistical language model [17] are out of scope of the paper. We omit also the phase of variable/function detection, which is an essential step before type recovering, this work can be referenced in [8] for example. From now on, unless otherwise stated, the target language is C which is also the target language of almost all research papers and tools in the domain.

## 2.1. Initial work

Though earlier ideas have been proposed in another context [3], the research in recovering types from low-level languages may begin with the classic paper of Mycroft [5] in his interest of decompilation. The principal idea is similar to which have done by Damas-Hindley-Milner [1, 2] in the ML language: types of variables and functions are checked/referenced automatically from how they are used in the program's source code. For example, given an expression

$$x + y$$

then at least  $x$  or  $y$  must have integer type, it is impossible that both of them are pointers since adding two pointers doesn't type check.

The method of Mycroft has several limits, as pointed out by Van Emmerik [9]. One of them comes from the fact that the low-level languages take care mostly on the value of the computation, then (the result of) an expression can be used in several ways and it behaves as different type in each case (low-level polymorphic). Let's consider an assignment

$$p' = p + n$$

where  $\vdash p: \text{ptr}(S)$  ( $p$  is of type pointer to a struct  $S$ ) and  $\vdash n: \text{int}$ , then Mycroft's rules derive  $\vdash p': \text{ptr}(S)$  since  $p+n$  is considered as the offset calculation to access some element of an array of  $S$ . But  $p+n$  can be also the offset calculation to access some field of type `int` of  $S$ , then  $\vdash p': \text{ptr}(\text{int})$ .

To overcome these problems, Van Emmerik has proposed a *data-flow based* (contrast with Mycroft's *constraint based*) approach where type information of an object will be refined gradually, instead of binding it early to some fixed type. He proposed using *subtype lattices* to express the preciseness of type information:  $p'$  will not

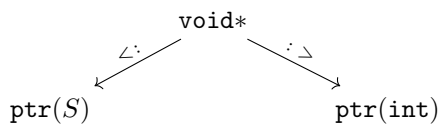


Figure 1. A subtype lattice

be early bound as  $\text{ptr}(S)$ , instead  $\vdash p': \text{void}^*$  (adding

integer to pointer does not result in pointer of the same type) where  $\text{ptr}(S) <: \text{void}^*$ . The precise type is only assigned later, when met with  $\text{ptr}(\text{int})$ , derived from another use, e.g.:

$$*p' + m$$

where  $\vdash m: \text{int}$ , it then derives  $\vdash p': \text{ptr}(\text{int})$ , finally  $\vdash p': \text{ptr}(\text{int})$  since  $\text{ptr}(\text{int}) = \text{ptr}(\text{int}) \sqcap \text{void}^*$ .

The lack of an IR with well-defined semantics limits Van Emmerik's work, he had to use ad-hoc type patterns to recognize and propagate type/subtype relations.

## 2.2. Improvement

Lee et al. [13] had the same idea about using type lattice to represent the preciseness of type information, but they did not work directly on machine language, an IR named BIL (BAP Instruction Language) has been used instead. This make the type analysis more flexible,

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Table Head	Table Column Head		
	Table column subhead	Subhead	Subhead
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<sup>a</sup>Sample of a Table footnote.

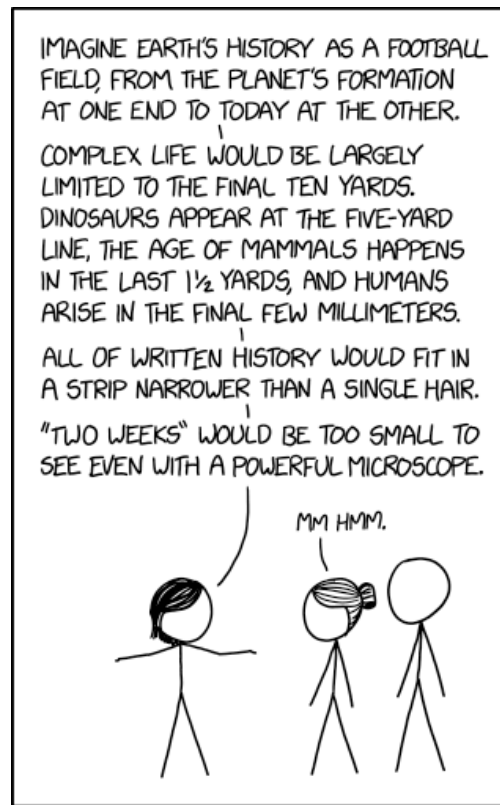
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## Acknowledgment

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## References

- [1] R. Milner. “A Theory of Type Polymorphism in Programming”. In: *Journal of Computer and System Science* 17 (1978), pp. 348–375.
- [2] L. Damas and R. Milner. “Principal Type-Schemes for Functional Programs”. In: *POPL*. 1982.
- [3] O. Shivers. “Data-Flow Analysis and Type Recovery in Scheme”. In: *Topics in Advanced Language Implementation*. MIT, 1990.
- [4] C. Cifuentes. “Reverse Compilation Techniques”. PhD thesis. 1994.



GEOLOGISTS ALWAYS TRY THIS WHEN THEY'RE LATE TURNING SOMETHING IN.

Figure 2. Example of a figure caption.

- [5] A. Mycroft. “Type-Based Decompilation (or Program Reconstruction via Type Reconstruction)”. In: *ESOP*. 1999.
- [6] B. Schwarz, S. Debray, and G. Andrews. “Disassembly of Executable Code Revisited”. In: *WCRE*. 2002.
- [7] M. Dalla Preda and R. Giacobazzi. “Semantic-Based Code Obfuscation by Abstract Interpretation”. In: *ICALP*. 2005.
- [8] G. Balakrishnan and T. Reps. “DIVINE: Discovering Variables IN Executables”. In: *VMCAI*. 2007.
- [9] M. Van Emmerik. “Static Single Assignment for Decompilation”. PhD thesis. 2007.
- [10] Y. Zhou, A. Main, Y. X. Gu, and H. Johnson. “Information Hiding in Software with Mixed Boolean-Arithmetic Transforms”. In: *WISA*. 2007.
- [11] C. Collberg and J. Nagra. *Surreptitious Software: Obfuscation, Watermarking, and Tamperproofing for Software Protection*. 1st. Addison-Wesley Professional, 2009.
- [12] A. R. Bernat and B. P. Miller. “Anywhere, Any-Time Binary Instrumentation”. In: *PASTE*. 2011.
- [13] J. Lee, T. Avgerinos, and D. Brumley. “TIE: Principled Reverse Engineering of Types in Binary Programs”. In: *NDSS*. 2011.
- [14] K. Anand et al. “A Compiler-level Intermediate Representation based Binary Analysis and Rewriting System”. In: *EuroSys*. 2013.

- [15] K. ElWazeer, K. Anand, A. Kotha, M. Smithson, and R. Barua. “Scalable Variable and Data Type Detection in a Binary Rewriter”. In: *PLDI*. 2013.
- [16] J. Caballero and Z. Lin. “Type Inference on Executables”. In: *ACM Computing Surveys* 48.4 (2016).
- [17] O. Katz, R. El-Yaniv, and E. Yahav. “Estimating Types in Binaries using Predictive Modeling”. In: *POPL* (2016).
- [18] M. Noonan, A. Loginov, and D. Cok. “Polymorphic Type Inference for Machine Code”. In: *PLDI*. 2016.
- [19] E. Robbins, A. King, and T. Schrijvers. “From MinX to MinC: Semantics-Driven Decompile of Recursive Datatypes”. In: *POPL*. 2016.
- [20] T. Blazytko, M. Contag, C. Aschermann, and T. Holz. “Syntia: Synthesizing the Semantics of Obfuscated Code”. In: *USENIX Security*. 2017.
- [21] N. Eyrolles. “Obfuscation with Mixed Boolean-Arithmetic Expressions: reconstruction, analysis and simplification tools”. PhD Thesis. Université Paris-Saclay, 2017.
- [22] S. Banescu and A. Pretschner. “A Tutorial on Software Obfuscation”. In: *Advances in Computers*. Vol. 108. Elsevier, Jan. 2018, pp. 283–353.
- [23] A. Maier, H. Gascon, C. Wressnegger, and K. Rieck. “TypeMiner: Recovering Types in Binary Programs Using Machine Learning”. In: *DIMVA*. 2019.
- [24] S. B. Yadavalli and A. Smith. “Raising Binaries to LLVM IR with MCTOLL (WIP Paper)”. In: *LCTES*. 2019.
- [25] R. David, L. Coniglio, and M. Ceccato. “QSynth - A Program Synthesis based approach for Binary Code Deobfuscation”. In: *BAR*. 2020.
- [26] *Ghidra*. URL: <https://ghidra-sre.org/>.
- [27] *Hex-Rays Decompiler*. URL: <https://www.hex-rays.com/>.
- [28] *JEB Decompiler*. URL: <https://www.pnfsoftware.com/>.
- [29] *Tigress: A Source-to-Source-ish Obfuscation Tool*. URL: <https://tigress.wtf>.