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Supporting Operating System Kernel Data Disambiguation Using Points-to Analysis
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ABSTRACT
Generic pointers scattered around operating system (OS) kernels make the kernel data layout ambiguous. This limits current kernel integrity checking research to covering a small fraction of kernel data. Hence, there is a great need to obtain an accurate kernel data definition that resolves generic pointer ambiguities, in order to formulate a set of constraints between structures to support precise integrity checking. In this paper, we present KDD, a new tool for systematically generating a sound kernel data definition for any C-based OS (e.g. Windows and Linux), without any prior knowledge of the kernel data layout. KDD performs static points-to analysis on the kernel’s source code to infer the appropriate candidate types for generic pointers. We implemented a prototype of KDD and evaluated it to prove its scalability and effectiveness.

Categories and Subject Descriptors
D2.7 [LOGICS AND MEANINGS OF PROGRAMS]: Program analysis; D4.6 [Operating Systems]: Security kernels.

General Terms
Performance, Security, Languages.

Keywords
Systematic kernel data integrity checking, points-to analysis.

1. INTRODUCTION
It is a very challenging task to verify the integrity of OS kernel data. An OS kernel has thousands of data structures that have direct and indirect relations between each other, with no explicit integrity constraints. In Windows and Linux OSs, from our analysis, nearly 40% of the structure relations are pointer-based relations (indirect relations), and 35% of these pointer-based relations are generic pointers (e.g. null pointers that do not have values, and void pointers that do not have associated type declarations in the source code). Such generic pointers get their values and thus types only at runtime according to the calling context. This makes kernel data a rich target for malware that exploits the pointer relations between data structures to compromise the kernel. Current kernel data integrity checking research [2; 4] is limited in solving those problems. This is because they depend on their prior knowledge of the kernel data layout to manually resolve the ambiguous pointer-based relations, and thus they only cover a small fraction of kernel data structures that relate to well-known objects e.g. processes and threads [3]. This results in limited protection and inability to detect zero-day threats, raising the need to get an accurate kernel data definition that resolves the generic pointers ambiguities.

In this paper, we introduce KDD (Kernel Data Disambiguator), a new static analysis tool that can generate a sound kernel data definition for any C-based OS (e.g. Windows and Linux), without any prior knowledge of the OS kernel data layout. KDD disambiguates the pointer relations including generic pointers - to infer their candidate types/values - by performing static points-to analysis on the kernel’s source code. KDD is able to scale to the enormous size of kernel code, unlike many other points-to analysis tools. In KDD, precision is an important factor; we want the most precise points-to sets to be computed. As the analysis is done offline and just once for each kernel version, performance is not such an important factor. To meet our requirements, we designed and implemented a new points-to analysis algorithm that has the ability to provide interprocedural, context- and field-sensitive, and inclusion-based points-to analysis for large programs that contain millions lines of code e.g. OS kernel.

2. BACKGROUND
C-based OSs use C structures heavily to model objects. They also use pointers extensively to emulate object-oriented dispatch, avoid expensive copying of large objects, implement complex data structures. Moreover, objects can be cast to multiple types during their lifetime, and a pointer deposited in a field under one object may be read from a field under another object. This makes the analysis of kernel’s data structures a non-trivial task. To get a concrete idea of the generic pointers problem, Figure 1 shows exemplar C code implementing pointers of the sort found in a typical OS. We discuss in it the context of three problems.

Void pointers; the problem with ‘void’ is that the target object type(s) can only be identified at runtime. From our example, UniqueProcessId is void *. However if we analyse the code, we find that it indirectly points to another structure. The wide use of void pointers hinders performing systematic integrity checks on kernel data, where there are no type constraints for void *. Null Pointers; null pointers are used heavily to implement linked lists. The C definition makes a linked list points to itself, but actually during system runtime it points to a specific object type according to the calling context. Procedure UpdateLinks, from our example, is used to update the objects’ list structured in _LIST_ENTRY (doubly-linked list). However, the objects structured in this list can be recognized only during runtime. Identifying type of the object that a linked list may hold at the offline analysis phase helps significantly in identifying a set of constraints on the runtime objects to detect invalid pointer dereferencing. Casting; casting induces relationships between objects that may appear to
be unrelated, enabling hackers to exploit data structures layout in physical memory. DebugPort, from our code, is declared as an integer; however it is being cast to be a pointer to a data structure.

typedef struct _LIST_ENTRY {
    struct _LIST_ENTRY *Flink;
    struct _LIST_ENTRY *Blink;
} LIST_ENTRY, *PLIST_ENTRY, *RESTRICTED_POINTER;
typedef struct _EPROCESS {
    int * handle;
    } ExHandle;

void CreateProcess(PPEPROCESS p_ptr) {
    p_ptr = (PPEPROCESS)malloc(sizeof(EPROCESS));
    updatelinks(&ptr->ActiveProcessLinks, &PsActiveProcessHead);
    return (PEPROCESS) malloc(sizeof(EPROCESS));
}

Figure 1. Example reflecting use of generic pointers.

Pointer analysis algorithms for C programs have been studied intensively over the last two decades. Their use has predominantly been for compiler optimizations and their main goal has thus been performance. Some work has attempted performing field and context sensitivity analysis on large programs [1; 7]. However none has been shown to scale to large programs context sensitivity analysis on large programs [1; 7]. However all of these approaches code with a high precision rate. Kernel data integrity checking has none has been shown to scale to large programs

3.2 Indirect Inclusion-Based Relations

Indirect relations (generic pointer dereferencing) cannot be computed from the AST directly. We have developed a new points-to analysis algorithm to statically analyse the kernel’s source code to get an approximation for every generic pointer dereferencing based on Anderson’s approach [1]. We consider all forms of assignments and function calls. Data structures are flattened to a scalar field. Type casting is handled by inferring locations accessed by the pointer being cast. Kernel objects are represented by their allocation site according to the calling context. The target graph of this step is $G(N, E)$, where $N$ is the set of nodes representing global and local variables, fields, array elements, procedure arguments/parameters and function return. $E$ is a set of directed edges across nodes representing, assignments and function calls. The graph nodes have four types and edges also have four types. Nodes - a node is one of: (i) Variable Node; represents variables including parameters. (ii) Field Reference Node; represents structure’s fields. Each field reference node has an associated parent node. (iii) Function Call Node; represents a function name and an index; index = 1 if the node represents a function return, otherwise index = i, where i is the index of formal-in argument – i.e. given a function call $G(\text{arg}1, \text{arg}2)$ in this case we will have two nodes $G.1$ and $G.2$ representing passed arguments $\text{arg}1$ and $\text{arg}2$, respectively. (iv) Cast Node; represents explicit casting where the type of the node is the typecast and the name is the casted variable or function. Edges - an edge may be: (i) Points-to edge; represents points-to relations between two nodes according to the edge direction. (ii) Inlist edge; represents a points-to relation between two nodes but on a local scope, thus if $\exists$ node A has inlist edge to node B, then B ∈ pts(A) where pts(A) means the points-to set of A. (iii) Outlist edge; is not a relation edge, but represents a directed path between two nodes that are used to achieve the points-to analysis. (iv) Parent-child edge; represents relation between parent and child – i.e. relation between structure and fields, or array and elements.

The type-graph of the indirect relations is created and refined by our points-to analysis algorithm in a three step process: Intraprocedural Analysis, Interprocedural Analysis, and Context-Sensitive Points-To Analysis. These steps are discussed below.

3.2.1 Intraprocedural Analysis

The goal of this phase is to compute a local type-graph without information about caller or callee. KDD takes the AST file as input and outputs an initial graph, as follows: (i) Variables - create a node for each variable declaration and check the function scope to find out if it is a local or global variable. (ii) Procedure Declaration; create a node for each formal-in parameter; (iii) Call; create node for each formal-in argument (if not already created), in addition to a dummy node for each formal-in argument represented by its index in the procedure. These dummy nodes will be used in the interprocedural analysis phase to create an implicit assignment relation between the formal-in arguments and formal-in parameters. (iv) Assignments; create nodes for the left and right hand sides, if not already created. (iv) Returns; create two nodes; one for the return statement itself and the other for the returned value inside the called procedure. KDD then builds the initial edges at this step by computing a transfer function (TF) for each procedure, procedure call,
assignment, and return statement, as described in table 1. TF is a formal description for the relation between the nodes created for each of the previous entities. In our motivating example from Section 2, consider the call to the function UpdateLinks, where the formal-in parameters are (src, tgt), and the actual passed arguments are (&ActiveProcessLinks, &PsActiveProcessHead). UpdateLinks also contains explicit assignment statements (src→ Flink = tgt→Flink; tgt→Blink = src→Blink). KDD computes the transfer function (TF) for those statements as shown in Figure 2 (a) and Figure 2 (b), respectively. For the return node, given this fragment of code UniqueThreadId = ExHandler(), the computed TF is shown in Figure 2 (c).

Table 1. Transfer function description.
Local points-to sets pts, constraints between nodes, and edges (→ a directed inlist edge between two nodes, ← a directed outlist edge).

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Description</th>
<th>Edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>proc(p)</td>
<td>relation between parameters and the dummy node that hold the indexes of the parameters. Edges: inlist edge between each formal-in parameter node and its relevant dummy node, and outlist edge from the dummy node to its relevant formal-in parameter node.</td>
<td>pts(proc:1) proc(p) proc:1 proc:p proc:1 proc:p</td>
</tr>
<tr>
<td>proc(p)</td>
<td>relation between left and right hand sides (HSs) of the assignment statement. Edges: inlist edge from left HS to right HS, and outlist edge from the right HS to left HS.</td>
<td>pts(proc:1) proc:p proc:1 proc:p</td>
</tr>
<tr>
<td>proc(q)</td>
<td>relation between the formal-in arguments nodes and dummy nodes. Edges: inlist edge between each argument node and its relevant dummy node.</td>
<td>pts(proc:1) proc:p proc:1 proc:p</td>
</tr>
<tr>
<td>proc(q)</td>
<td>relation among left HS, the procedure return node and the returned value node. Edges: inlist edge between the left HS and the return node, inlist edge between the return node and returned value node and outlist edge between the return node and the left HS.</td>
<td>pts(proc:1) proc:p proc:1 proc:p</td>
</tr>
</tbody>
</table>

Figure 2. Intraprocedural analysis graph: solid arrows inlist edges and dashed outlist edges; dashed ovals dummy nodes.

3.2.2 Interprocedural Analysis
In this phase we perform an interprocedural analysis that enables us to perform points-to analysis across different files to perform a whole-program analysis. We refine the initial type-graph by incorporating interprocedural information from the callees of each procedure. The result of this phase is a graph that computes the calling effects (returns, arguments and parameters), but without any calling context information yet. This is done by propagating the local points-to sets (inlist edges) computed at the intraprocedural analysis step to their use sites consistently with argument index in the call site, as shown in figure 3. Thus we can map between the procedure arguments and parameters.

3.2.3 Context-Sensitive Points-To Analysis
The key in achieving context-sensitivity is to obtain the return of procedures according to the given arguments combined with the call site. Points-to analysis is performed in three sub-steps:

1) Points-to Analysis: a well-known complication in this analysis is the order of which nodes will be analysed first, where this can greatly affect performance. A good choice is to analyse nodes in a topological order [6], by building a Procedure Dependency Graph (PDG). This graph enhances the analysis by providing the appropriate analysis sequence that result in precise points-to analysis. We start with the top node that does not have any dependencies, and thus we guarantee that each node has its inlist nodes already analysed before proceeding with the node itself. We expand the local dereferencing of the pointers to get the points-to relations between the caller and callee. We propagate the points-to set of each node into its successors accumulating to the bottom node. For acyclic points-to relations, pointers are analysed iteratively until points-to sets are fully traversed. For recursions, we analyse pointers in each recursion cycle individually.

2) Graph Unification: consider the following piece of code from the motivating C code example: UpdateLinks (&p→->ActiveProcessLinks, &PsActiveProcessHead). We pass an object (data structure) to the procedure; however the procedure UpdateLinks manipulates the fields of the passed object e.g. Flink and Blink. To solve this problem, we apply a unification algorithm to the type-graph, as follows: given node A with points-to set S and T ∈ E, if T has child-relation edge with f; we copy f to A, create a child-relation edge between f and A, and also create points-to edge from A/f to T/f, as shown in Figure 4.

3) Context-Sensitivity: to achieve context-sensitivity, we use the transfer function for each procedure call and apply its calling contexts, to bind the output of the procedure call according to the calling site. The points-to edge here is a tuple (n, v, c) representing that a pointer n points to variable v at context c, where the context is defined by a sequence of functions and their call-sites to find out valid call paths between nodes. Performing context-sensitive analysis solves two problems: the calling context and the indirect (implicit) relations between nodes. These indirect relations are calculated for each of the two nodes that are in the same function scope but not included in one points-to set. Such that, ∀ two nodes n and v where v ∈ pts(n) and v and n has different function scope, check the function scope of n and x where x ∈ pts(v), if the function scope is the same then create a points-to edge between n and x. Figure 5 shows the final context-sensitive analysis for UpdateLinks. Note an indirect points-to relation from PsActiveProcessHead to ActiveProcessLinks.

Finally, we write the type-graph. We replace each variable node with its data type and for fields and array elements we add the declared parent type.
AST as the basis for points-to analysis. The compact and syntax-key to achieve this scalability and high performance was by using type-graph for a large-scale C program such as an OS kernel. A Thus KDD is able to scale to produce a detailed, highly accurate well-known object types and precision was around 96%. We measured precision for the members as there is no clear description for these members soundness. We could not measure the precision for nearly 60% of these indirect relations in both kernels. KDD successfully deduced inferred by KDD and the manual efforts of OS experts to solve results, we performed a comparison between the pointer relations generated type graph. To evaluate the effectiveness of KDD’s any security application that wants to make use of KDD’s analyzing kernels is acceptable and does not present a problem for just once or each kernel version, performance overhead of Linux kernel. As our points-to analysis is performed offline and scales to the very large size of such OSs. KDD needed around 28 hours to analyze the WRK and around 47 hours to analysis the Linux kernel. As our points-to analysis is performed offline and just once or each kernel version, performance overhead of analyzing kernels is acceptable and does not present a problem for any security application that wants to make use of KDD’s generated type graph. To evaluate the effectiveness of KDD’s results, we performed a comparison between the pointer relations inferred by KDD and the manual efforts of OS experts to solve these indirect relations in both kernels. KDD successfully deduced the candidate target type/value of these members with 100% soundness. We could not measure the precision for nearly 60% of the members as there is no clear description for these members from any existing manual analysis. We measured precision for the well-known object types and precision was around 96%.

Thus KDD is able to scale to produce a detailed, highly accurate type-graph for a large-scale C program such as an OS kernel. A key to achieve this scalability and high performance was by using AST as the basis for points-to analysis. The compact and syntax-free AST improves time and memory usage efficiency of the analysis. To the best of our knowledge, there is no similar research in the area of systematically defining the kernel data structure with the exception of KOP [3]. However, KOP is limited in that the points-to sets of KOP are not highly precise; analysis performance overhead is very high; and KOP uses a medium-level intermediate representation which complicates the analysis and results in improper points-to sets.

5. SUMMARY

The wide existence of generic pointers in OS kernels makes kernel data ambiguous and thus hinders current kernel data integrity research from providing the preemptive protection. KDD is a new tool that has the ability to generate a sound kernel data structure definition for any C-based operating system, without any prior knowledge of the OS. Our experiments have shown that the KDD-generated type-graph is accurate and solves the generic pointer problem with high rate of soundness and precision. To the best of our knowledge, KDD is the only tool that can scale to produce a detailed, highly accurate type-graph for C-based OSs.

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6. REFERENCES


Table 2. Soundness and Precision Results running KDD on a suite of benchmark C programs.

<table>
<thead>
<tr>
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