Graph-based automatic program separation

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Abstract

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3.1 Program dependence graph

Program Dependence Graph(PDG) plays a key role in our separation framework. To build a PDG for a large program with multiple functions, we first build a PDG for each function, which means we first model all the intra-procedural dependences. Then, based on the caller-callee relationships, we build corresponding parameter trees[1] to model the inter-procedural dependences. We also use tree structures to represent the global data structures, and construct the data dependences between the global variables and their caller functions.

We develop a toolchain which can build instruction-grained PDGs for LLVM IRs. Our toolchain wraps up each IR instruction as a graph node, and adds two kinds of auxiliary nodes to help represent the inter-procedural

dependences. So, we have three kinds of node in a PDG in total:

(1) **instruction node**: used to represent an LLVM IR instruction;

(2) **data node**: used to represent the data in memory;

(3) **parameter tree node**: used to build the parameter trees.

Accordingly, we have four kinds of edges:

(1) **control dependence edge**: used to represent a control dependence;

(2) **data dependence edge**: used to represent a data dependence;

(3) **parameter tree edge**: used to connect the parameter tree nodes;

(4) **call edge**: used to connect the call site with the entry site of callee function. For indirect calls, we use a type-based approximation to connect the call site with all possible target callees with the same type.

3.1.1 Modeling intra-procedural dependences

The intra-procedural dependences consist of both control dependences and data dependences. The control dependences within a function can be captured easily with the classical post-dominator-tree-based algorithm[2]. Computing the data dependences is a little harder since we need to process two different kinds of data dependences separately, the **def-use dependences** and the **flow dependences**(**true data dependences**). The def-use dependence represents the data dependency between two statements with the definition-use association(DUA,see Fig 1.a), and the flow dependence represents the dependency between memory read and write operations(read-after-write,see Fig 1.b). In this paper, both the **anti-**dependence (write-after-read) and the **output-**dependence(write-after-write) are not in our consideration, and we only compute the flow dependence.

The definition-use dependences can be detected easily by finding all variables in a statement and then adding a dependence between it and the

```
int x = 0;      /*define x*/
...
int y = x + 1; /*use x*/
...
```

(a) def-use dependence

```
int a = 3;
int *p = &a;
*p = 5;      /*memory write*/
int b = a;   /*memory read*/
```

(b) flow dependence

Figure 1: An example of two kinds of data dependences

statement that defines the variable. For flow dependencies, since they only exist between the memory read and write statements, our algorithm for computing all of intra-procedural flow dependencies can be described as follows:

Step 1: Check each memory operation in the program, if it is a memory read, do Step 2; otherwise, continue to check the next memory operation.

Step 2: For each memory read r_i, check each memory write operation w_i in this function, if r_i and w_i access the same memory location, $r_i \rightarrow w_i$ is a flow dependence. The alias analysis algorithm is required here, in our work, we use the DSA algorithm[3] to help compute the aliases because it is a kind of open-source, context-sensitive and field-sensitive algorithm that can be applied to large server applications[4].

3.1.2 Modeling inter-procedural dependences

The inter-procedural data dependency fully depends on the function parameter passing. So, the core part of modeling inter-procedural data dependency is how to represent the data dependency between the **actual**

parameters(arguments) and the **formal parameters**. If the function parameter is a pointer, we need to further model the dependency associated with the value that the pointer points to. To represent the data layout of parameters in memory as precisely as possible, we model 4 parameter trees for each parameter:

actual-in tree: used to represent a new actual parameter before entering the callee function;

actual-out tree: used to represent the actual parameter when a call is finished;

formal-in tree: the callee analog of actual-in tree, used to represent the formal parameter before the callee execution;

formal-out tree: the callee analog of actual-out tree, used to represent the formal parameter after the callee execution.

For each function[1] f, we only need to build its formal-in and formal-out trees once because f only has one function body. On the other hand, the number of actual-in and actual-out trees depends on how many calls we have in a program. If f is directly called by another function q, we build the actual-in and actual-out trees at the call site which is within q. So, each direct call for f matches exactly one pair of formal-in and formal-out trees. However, if f is called indirectly, it is impossible for us to exactly locate the position of callee function. Our solution is to approximately retrieve all possible candidate functions with the same type as f and build actual-in/out trees for each of them, which means some redundant actual trees will be built inevitably.

The process of building a parameter tree is shown in Algorithm 1. Each incoming parameter p corresponds to a root. If p is a pointer, we insert the value that p points to into the tree as the only child of p and process this value to build subtrees recursively; otherwise if p is a struct, we retrieve each field f_i in p and insert f_i as a child of p, and then use f_i as input to

[1]Library functions(e.g.scanf, printf, exit...) will not be unfolded as subgraphs but represented as common nodes.

build a subtree; if p is neither a pointer nor a struct, which means it must be a variable of atomic type[2](e.g. int, float, char...), p will be inserted as a leaf. Actually the parameter tree for an atomic variable always shrinks to a single node.

Algorithm 1: building a parameter tree

BuildTree(p, T)
Input : p– parameter; T– a pointer which points to the tree root
Output: a constructed tree represented by T

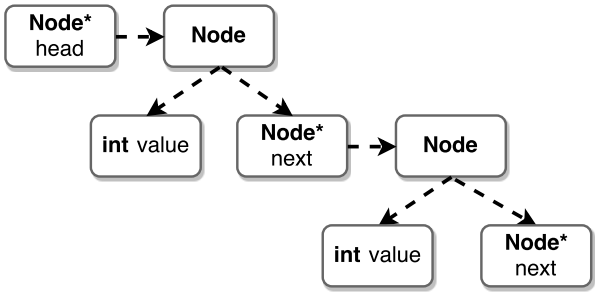
```
T → root = p;
if p is a pointer then
    T → root → firstchild = dereference(p) ;          /* insert *p */
    BuildTree(dereference(p), T → root → firstchild);
else
    if p is a struct then
        for each field f_i in p do
            T → root → appendchild(f_i);
            BuildTree(f_i, T → root → getchild(i));
        end
    else
        ;                                   /* atomic parameter */
    end
end
```

One problem about representing parameters with tree structures is some parameters may have recursive data structures(e.g. linked list) that can lead to parameter trees of infinite depth. To solve this problem Graf[1] proposes an algorithm to unfold the recursive data structures. In our framework, we directly borrow that algorithm to help build parameter trees. A example of building parameter trees with recursive data structures is listed in Figure 2.

[2]For simplicity, we take `string` as an atomic type also.

```
struct Node*{
  int value;
  Node *next;
};

struct Node *head = NULL;
head = malloc(sizeof(struct Node));
buildlist(head);
...
```



(a) a linked list program (b) an unfolded parameter tree

Figure 2: An example of parameter trees with recursive data structure

We also use the tree data structure to model the global variables for better field-sensitivity. The algorithm for building the global variable trees is completely the same as building the function parameter trees.

3.1.3 Example: encrypt a password

Let us see a real example. The toy program in Figure 2 includes a function with simple greeting, a function for password encryption and the main function. In line 2, we mark array `password` as a piece of sensitive data. Figure 3 is the PDG model for this toy program. We omit most of the simple intra-dependences, and only keep the most interesting part about how to use parameter trees to represent the inter-procedural data dependency.

```
1  static char username[20];
2  static char __attribute__(sensitive) password[20];
3
4  int greeter(char *str){
5    if(str == NULL)
6     return 1;
7    printf("Welcome %s!"\n, str);
8    return 0;
9  }
10
11 int encrypt(char *str,int key){
12   unsigned int i;
```

```
13    for(i = 0; i < strlen(str); ++i){
14      str[i] = str[i] - key;
15    }
16    return 0;
17  }
18
19  int main(){
20    printf("Create your username: \n");
21    scanf("%s", username);
22    if(greeter(username) == 1)
23      printf("Invalid user!\n");
24    printf("Enter your password: \n");
25    scanf("%s", password);
26    printf("password:%s\n", encrypt(password,5));
27    return 0;
28  }
```

Figure 2. A toy C program to encrypt a password

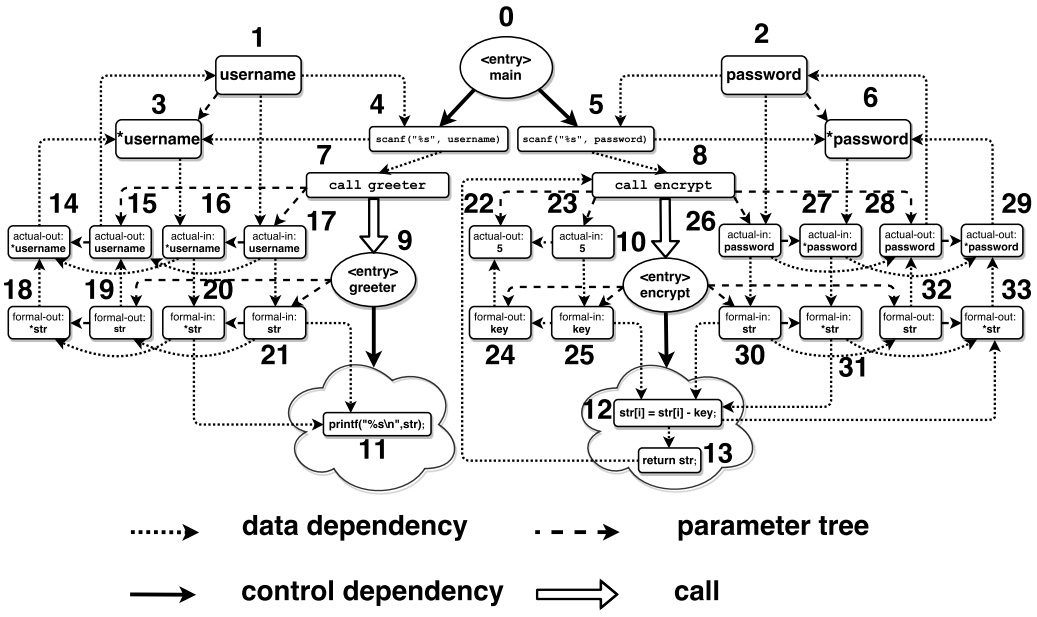


Figure 3: The program dependence graph of our toy program.

In Figure 3, we construct two trees for global arrays `username` and `password` separately. Considering all arrays passed to functions are converted into pointers in C, we directly represent them with the form of `char*` instead of `char[]`, and by doing this we can show the data dependency better. As you can see on the upper-left part, node 1, which is the root of the global variable tree for `username`, represents the pointer that points to the username string; while node 3 represents the content that pointer points to, i.e., the string itself. By algorithm 1 clearly node 3 is the child of node 1, and also a leaf since we take `string` as an atomic type just as we mentioned before. In the main function, we need to set up a def-use data dependence edge ($1 \rightarrow 4$), and a flow dependence data dependence edge ($4 \rightarrow 3$) since the operation `scanf` uses the pointer "username" first and then modifies the value that pointer "username" points to.

Next, we have a data dependence edge ($4 \rightarrow 7$) because we take the call operation(node 7) as a kind of use of "username". We use a call edge($7 \rightarrow 9$) to connect the call site(node 7) in the caller function(`main`) and the entry node of the callee function(`greeter`). The function body of `greeter` is abstracted as a cloud-like region, connected with its entry node through an abstract control dependence edge ($9 \rightarrow 11$).

Now we can use parameter trees to represent the parameter passing between `main` and `greeter`. We let the call node(node 7) dominate the actual-in(node 16, node 17) and actual-out(node 15, node 14) trees,and the entry node of greeter(node 9) dominate the formal-in(node 21 and 20) and formal-out(node 19 and 18) trees. There are two kinds of data flow when the parameter is a pointer: one is the data flow of the pointer itself, and the other is the data flow of the value that pointer points to(pointee). On this graph, the data flow of the pointer itself(username) can be represented by a node sequence $1 \rightarrow 17 \rightarrow 21 \rightarrow 19 \rightarrow 15 \rightarrow 1$, which is a loop actually. Accordingly, the data flow of the pointee of "username" can be represented with the sequence $3 \rightarrow 16 \rightarrow 20 \rightarrow 18 \rightarrow 14 \rightarrow 3$. However, there is only memory read(node 11) but no write operation in function greeter, so we only have two data dependence edges ($21 \rightarrow 11$) and ($20 \rightarrow 11$), which both come from the caller to callee.

The PDG construction for (encrypt) is similar. The first parameter is just an integer so each parameter tree is simply constructed as a single

node. There is a data dependence edge (25 → 12) since the formal parameter "key" is read by statement "`str[i] = str[i] - key;`". One important data dependence edge in `encrypt` is (12 → 33), which represents that we update the buffer that the pointer "str" points to inside the callee function. Finally, we have a a data dependence edge (13 → 8) to represent the data flow of return value.

3.2 PDG-based separation algorithm

After we have a PDG for a program, we can separate this program into two slices by partitioning its PDG into two cuts. Simply speaking, we first annotate some sensitive data in the program with the `__attribute__` grammar(see line 2 in Figure 2) and take the corresponding graph nodes as the source, and then start from the source nodes to do a greedy coloring along the data dependence edges on the graph. After the coloring finished, we get two sets of graph nodes, one consists of all the colored nodes and the other consists of all the uncolored nodes. In the set of the colored nodes, we check each node one by one, if it corresponds to a global variable, we directly mark that global variable as sensitive, and if it corresponds to a statement within a function, we mark that function as sensitive. Ultimately, all the sensitive functions and global variables will be separated from the original input program as an independent slice, and we call this slice a "sensitive slice". On the other hand, the left global variables and functions that are non-sensitive form another slice, and we call it "non-sensitive slice" accordingly. A detailed description of our separation is in Algorithm 2.

Algorithm 2: PDG-based program separation

Program_Separate(*PDG*, *function_set*, *global_set*, *source_nodes*, *colored_nodes*, *Queue*)
Input :
PDG(*N*,*E*) — a directed graph which represents the whole input program *P*, where *N* is the set of nodes and *E* is the set of edges;
function_set — a set which contains all the functions in *P*;
global_set — a set which contains all the global variables in *P*;
source_nodes — a set which contains all the nodes that marked as "sensitive" on the PDG;
colored_nodes — a set which contains all the colored graph nodes during the coloring;
Queue — a priority queue used for the greedy graph coloring;
Output:
function_set — a set with all sensitive functions colored and non-sensitive functions uncolored;
global_set — a set with all global variables colored and non-sensitive global variables uncolored.

Initialization :

colored_nodes ← *source_nodes*;

current_node ← *NULL* ; `/* the node we are working on */`
foreach *node n in source_nodes* **do**
    Push(*Queue*, *n*);
    Color *n*;
    Insert(*colored_nodes*, *n*);
end
while *Queue is not empty* **do**
    current_node ← *Pop*(*Queue*);
    foreach *successor node* n_s *of current_node* **do**
        if s_n *is uncolored* **and** ($n \rightarrow n_s$) *is a data dependence edge* **then**
            Color n_s;
            Insert(*colored_nodes*, n_s);
            Push(*Queue*, n_s);
        end
    end
end
foreach *node c in colored_nodes* **do**
    Color c's corresponding function f_c in *function_set*;
    Color c's corresponding global variable g_c in *global_set*;
end

4 Inter-module communication

5 Evaluation

6 Conclusions

References

[1] J. Graf. Speeding up context-, object- and field-sensitive SDG generation. In *Proc. 9th IEEE International Working Conference on Source Code Analysis and Manipulation*. IEEE Computer Society, pages 105-114, 2010.

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[3] C. Lattner, A. Lanharth, V. Adve. Making context-sensitive points-to analysis with heap cloning practical for the real world. In *Proc. of PLDI*, 2007.

[4] I. Evans, F. Long, U. Otgonbaatar, H. Shrobe, M. Rinard, H. Okhravi, and S. Sidiroglou-Douskos. Control jujutsu: On the weaknesses of fine-grained control flow integrity. In *ACM SIGSAC Conference on Computer and Communications Security, CCS*, 2015.