Graph-based automatic program separation

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Abstract. This is abstract.

1 Introduction

2 Related work

3 Separation Framework

3.1 Program dependence graph

Program Dependence Graph(PDG) plays a key role in our separation framework. 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 some auxiliary data nodes to help represent the inter-procedural dependences. So, we have two kinds of node in a PDG:

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

(2) **data node**: used to represent: (1) global values; (2) auxiliary trees that called *parameter trees* for representing the parameter passing.

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) **connecting edge**: used to connect the corresponding data nodes to represent a complex global variable or a parameter tree;

(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.

Topologically, a PDG for a program with multiple functions is an inter-procedural extension of a program with only one function. So, accordingly, to build a PDG for a large program with multiple functions, we build a PDG for

each function first, and then "glue" these small PDGs together. In other words, we first model all the intra-procedural dependences. Then, based on the caller-callee relationships, we build the 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.

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[4]. Computing the data dependences is a little harder since we need to process two different kinds of data dependences separately. They are:

definition-use dependence: Given two instructions I_d and I_u, if a variable is defined in I_d, and then used in I_u, then we say there is a definition-use data dependence from I_d to I_u, noted as $I_d \rightarrow I_u$.

flow dependence: Given two instructions I_r and I_w, if I_w precedes I_r, and I_w modifies the data that I_r reads(RAW: read after write), then we say there is a flow dependence from I_w from I_r, noted as $I_w \rightarrow I_r$.

An example of two kinds of data dependences is listed in Fig.2.

```
A: %x = alloca i32, align 4
...
B: store i32 2, i32* %x, align 4
```

(a) a def-use dependence $A \rightarrow B$

```
A: store i32 2, i32* %x, align 4
...
B: %0 = load i32* %x, align 4
```

(b) a flow dependence $A \rightarrow B$

Fig. 2: An example of two kinds of data dependences

The definition-use dependences can be detected easily because LLVM uses the SSA form. So, in order to detect a definition-use data dependence, it suffices to retrieve each operand in an instruction I_u, and add a dependence from the instruction I_d that defines this operand to I_u.

For flow dependencies, since they only exist between the LLVM `store` instructions and `load` instructions, our algorithm for computing all of intra-procedural flow dependencies can be described as follows:

In procedure P, for each `load` instruction l_i, check each `store` instruction s_i in P, if l_i and s_i access the same memory location(e.g. `%x` in Fig.2 (b)), $s_i \rightarrow l_i$ is a flow dependence. The alias analysis algorithm is required here, in our work, we use the DSA algorithm[5] 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[6].

Once we finished constructing the PDG for each procedure, we can start to model the inter-procedural dependences to construct the ultimate PDG for the whole program.

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**. To achieve the field-sensitivity and represent the data layout of parameters in memory as precisely as possible, we use trees to model function parameters. In this paper, these trees are called *parameter trees*.

Once we construct the parameter trees for a parameter p, we can clearly represent the field-sensitive data flow in p's parameter passing by connecting its corresponding tree nodes. If p is a pointer, we need to further model the dependency associated with the value that p points to.

We model 4 parameter trees for each parameter in total. They are:

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

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

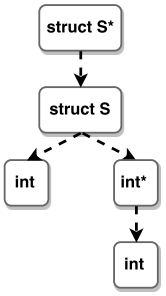
formal-in tree: the callee analog of actual-in tree, used to represent the formal parameter before the callee execution;

formal-out tree: the callee analog of actual-out tree, used to represent the modified 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.

Our algorithm for modeling a p's parameter tree is shown in Algorithm 1. The algorithm is fully based on p's type, noted as *type(p)*. First, we take *type(p)* as the tree root, if it is a basic type[2], we leave *type(p)* as a single leaf node and stop, and in this case all p's parameter trees shrink to single nodes accordingly; if p is a pointer, we insert *type(*p)* into the tree as the only child of *type(p)* and process *type(*p)* to build subtrees recursively; if *type(p)* is a structure type, we retrieve each field f_i in p and insert *type(f_i)* as a child of *type(p)*, and then use *type(f_i)* as the input to build a subtree. In Fig.4, we use a typical structure type to show how a type-based parameter tree looks like.

```
struct S{
  int i;
  int *p;
};
...
int a = 3;
struct S s = {2, &a};
struct S *sp = &s;
func(sp);
```



(a) sp: a pointer which points to a structure (b) the type-based parameter tree of sp

Fig. 4: Example: a type-based parameter tree

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. In our framework, we use the $k-$limiting approach[3] to forcibly expand the tree to level k only to prevent infinite expansions. For simplicity, we let k=1. An example of building a 1−limiting parameter tree for a recursive data structure is listed in Fig.6.

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

[2] In C, this means types formed by four basic type specifiers *char*, *int*, *float*, *double* and four modifiers *signed*, *unsigned*, *short* and *long*.

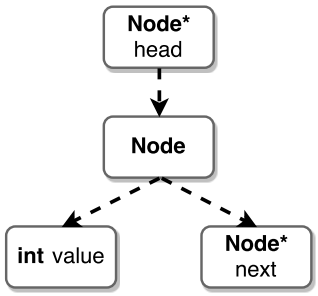
Algorithm 1: building a parameter tree

Parameter type t := *base type* | $t^{'}*$ | *struct* $\{t_1; t_2; \ldots; t_n\}$.
appendSubtree(*root*, t_1, t_2, ... , t_n) : append trees t_1, t_2, ... , t_n as the children of *root* .
buildTree(t)
switch t **do**
  case $t^{'}*$
    let *subtree* = *buildTree*($t^{'}$) in *appendSubtree*(t, *subtree*);
  end
  case *struct* $\{t_1; t_2; \ldots; t_n\}$
    let $subtree_1$ = *buildTree*(t_1) in
    let $subtree_2$ = *buildTree*(t_2) in
    ...
    let $subtree_n$ = *buildTree*(t_n) in
    appendSubtree(t, $subtree_1$, $subtree_2$, ... , $subtree_n$);
  end
  otherwise /* t is an atomic type */
    appendSubtree(t, *null*); /* Leave t as a leaf node */
  end
endsw

```
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

Fig. 6: 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.

indirect function call If a function 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.

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

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

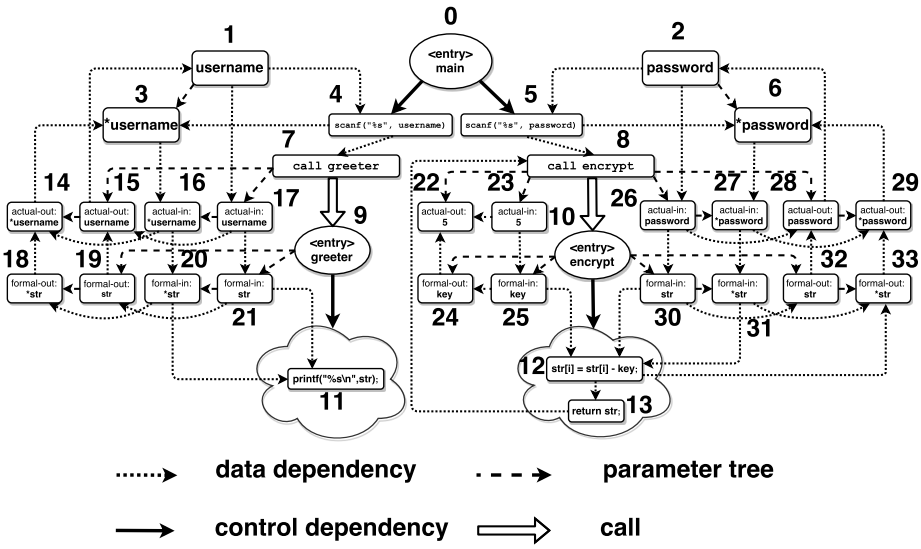


Fig. 7: The program dependence graph of our toy program.

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 $(25 \rightarrow 12)$ since the formal parameter "key" is read by statement "`str[i] = str[i] - key;`". One important data dependence edge in `encrypt` is $(12 \rightarrow 33)$, 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 $(13 \rightarrow 8)$ 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

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