Bridging the Semantic Gap Through Static Code Analysis

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April 10, 2012
Outline

1. Motivation
   - Introducing InSight
   - Why debugging symbols are insufficient

2. Static Code Analysis
   - Step 1: Points-to Analysis
   - Step 2: Establishing Used-as Relations

3. Implementation

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Virtual Machine Introspection (VMI) [Garfinkel and Rosenblum (2003)]

VMI describes the act of **examining**, **monitoring** and **manipulating** a virtual machine from the **vantage point** of a hypervisor.
Semantic Gap
[Chen and Noble(2001)]
Common Approach: utilize kernel debugging symbols

- Use symbols for:
  - Layout and size of kernel data structures
  - Virtual address of global variables and functions
- Emulate virtual-to-physical address translation in software

⇒ Complex engineering task
Introducing InSight
[Schneider et al.(2011)]

Features:

- Stand-alone VMI tool to bridge the semantic gap
- Uses debugging symbols as foundation
- Shell-like interface for interactive inspection
- JavaScript engine for automated analysis
- Works for x86 32 bit (w/ PAE) and 64 bit Linux guests
- Supports any hypervisor providing guest memory access
Introducing InSight (cont.)
[Schneider et al.(2011)]

Functionality so far

- Read objects from known locations with known type
- Follow typed pointer fields to further objects

But...
Why debugging symbols are insufficient

```c
struct list_head {
    struct list_head *next, *prev;
};

struct module {
    struct list_head list;
    char name[60];
    /* ... */
};

struct list_head modules;

struct module* find_module(const char *name)
{
    struct module *mod;
    list_for_each_entry(mod, &modules, list)
    {
        if (strcmp(mod->name, name) == 0)
            return mod;
    }
    return NULL;
}
```
Why debugging symbols are insufficient (cont.)

```c
struct module* find_module(const char * name)
{
    struct module * mod;
    /* Original code: list_for_each_entry(mod, &modules, list) */
    for (mod = ({
        const typeof(((typeof(*mod) *) 0)->list) * __mptr = ((&modules)->next);
        typeof(*mod) (*) (char *) __mptr - __builtin_offsetof(typeof(*mod), list));
    });
    __builtin_prefetch(mod->list.next), &mod->list != (&modules);
    mod = ({
        const typeof(((typeof(*mod) *) 0)->list) * __mptr = (mod->list.next);
        typeof(*mod) (*) (char *) __mptr - __builtin_offsetof(typeof(*mod), list));
    })
    {
        if (strcmp(mod->name, name) == 0)
            return mod;
    }
    return ((void *) 0);
}
```
Why debugging symbols are insufficient (cont.)
Example: `lsmod` in JavaScript
Manually apply expert knowledge

```javascript
function lsmod()
{
    // type of variable "modules" is list_head
    var head = new Instance("modules");
    var m = head.next;
    m.ChangeType("module");
    // offset for address correction
    var offset = m.MemberOffset("list");
    m.AddToAddress(-offset);
    // correct head as well for loop terminate
    head.AddToAddress(-offset);
    // iterate over all modules
    do {
        print(m.name + " " + m.args);
        m = m.list.next;
        m.ChangeType("module");
        m.AddToAddress(-offset);
    } while (m && m.Address() != head.Address());
}
```

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April 10, 2012
Summary

Problems
Runtime pointer and type manipulations are not reflected in the debugging symbols:

- type casts from void* pointers
- type casts from integer types
- pointer arithmetic
- variable length arrays

Possible solution
Static analysis of the kernel’s source code to detect such runtime operations and augment the debugging symbols
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Questions our code analysis can answer:

1. Is a global variable or structure field used as a type that differs from its declaration?
2. How to transform a source value (field/variable) to derive the next object’s address?

Our approach:

- Type centric analysis
- Captures arbitrary pointer arithmetic
- Over-approximation of possible pointer types
  → Increase object coverage at cost of type uncertainty

We call this the used-as analysis.
Used-As Analysis

**Prerequisites:**
- Kernel debugging symbols
- Pre-processed source code

**Involves two steps:**
1. **Points-To Analysis**
   - Detects memory aliasing between symbols (variables/pointers)
   - Reveals *indirect type usages* through local (pointer) variables
2. **Establishing used-as relations**
   - Find type usages contradicting their declaration
     → *type casts*
   - Record how value is transformed to target address
     → *pointer arithmetic*

```
struct module* find_module(const char * name)
{
    struct module * mod;
    /* Original code: list_for_each_entry(mod, &modules, list) */
    for (mod = ((
        const typeof(((typeof(*mod)) *) 0)->list) * __ptr = ((&modules)->next);
        (typeof(*mod)) * (char *) __ptr = __builtin_offsetof(typeof(*mod), list));
    )
    __builtin_prefetch(mod->list.next), &mod->list != (kmodules);
    mod = ((
        const typeof(((typeof(*mod)) *) 0)->list) * __ptr = (mod->list.next);
        (typeof(*mod)) * (char *) __ptr = __builtin_offsetof(typeof(*mod), list));
    ))
{
    if (strcmp(mod->name, name) == 0)
        return mod;
    }
    return ((void *) 0);
}
```
Step 1: Points-to Analysis

**Characteristics:**

- structure/union field sensitive
- intra-procedural
- control-flow insensitive
- works on complete C expressions:
  
  \[
  x = y + 8 \times \text{sizeof(int)};
  z = x \& \sim 0xFF;
  \]
  
  \[
  z \mapsto \{(y + 8 \cdot \text{sizeof(int)}) \& \sim0xFF\}
  \]

**Result:** transitive closure of points-to map
Step 2: Establishing Used-as Relations

Find used-as relations for

- global variables of pointer or integer type
- structure/union fields of pointer or integer type

Analysis overview:

1. Examine type usages under consideration of points-to map in
   - assignment statements
   - initializers
   - pointer dereferences after type casts
   - function parameters
   - return statements

2. Find mismatching source and target type

3. Identify corresponding context structure/union

4. Link alternative type along with arithmetic expression
   - to global variable or
   - to field of context structure/union
Step 2: Establishing Used-as Relations
Type usages

```
struct A { int value; struct A *next; };
struct B { void *data; }

struct A* func1(struct A *a) { return a; }

struct A* func2()
{
    struct B b;
    struct A a = { 0, b.data }; // initializer (struct)
    struct A *pa = b.data;     // initializer (variable)
    pa = b.data;               // assignment
    a = *((struct A*)b.data);  // dereference (*)
    ((struct A*)b.data)->value++; // dereference (->)
    pa = func1(b.data);        // function parameter
    return b.data;             // return statement
}
```

**Result:** Field ‘data’ of struct B having type void* is used as struct A* with expression (struct B).data.
Step 2: Establishing Used-as Relations
Achieving type context sensitivity

Problem

- Used-as relations are often unique to their context (embedding) type
- Propagating such relations to other contexts would increase ambiguity

Solution

- Copy embedded structures/unions uniquely for embedding type
- Record used-as relations for this copy’s members
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Extension of InSight for Used-as Analysis

Required extensions:
- **Consolidation** of types from debugging symbols
- **Parser for C** with GCC extensions
- **Semantic analyzer** for “type flow” within statements and expressions
- **Evaluator for C expressions**, including many GCC builtins
Results of Used-As Analysis

Experiments with Debian 6.0, AMD64, Kernel 2.6.32

- Analysis required < 20 min. for 20 mio. LoC (584 MB)
- 11,382 unique types in total

Used-as relations in...

- 233 of 23,949 global variables
- 225 of 3,012 unique struct/union types
- 812 struct/union unique types with 908 members
  - 541 struct list_head
  - 18 struct hlist_head
  - 15 struct rb_root
  - 7 struct device
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Manually apply expert knowledge

```javascript
function lsmod()
{
    // type of variable "modules" is list_head
    var head = new Instance("modules");
    var m = head.next;
    m.ChangeType("module");
    // offset for address correction
    var offset = m.MemberOffset("list");
    m.AddToAddress(-offset);
    // correct head as well for loop terminaten
    head.AddToAddress(-offset);
    // iterate over all modules
    do {
        print(m.name + " " + m.args);
        m = m.list.next;
        m.ChangeType("module");
        m.AddToAddress(-offset);
    } while (m && m.Address() != head.Address());
}
```
Example: `lsmod in JavaScript`

Automatic application of used-as relations

```javascript
function lsmod()
{
    // type of variable "modules" is list_head
    var head = new Instance("modules");
    // iterate over all modules
    var m = head.next;
    while (m.MemberAddress("list") != head.Address()) {
        print(m.name + " " + m.args);
        m = m.list.next;
    }
}
```
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- **Used-as analysis** captures type usages contradicting declared type
- Extracts arithmetic expression to retrieve target object address
- Extension of **InSight** mimics dynamic pointer manipulations through kernel
- Highly advanced approach for recreation of kernel state from hypervisor’s perspective

Released under GPLv2 license: https://code.google.com/p/insight-vmi/
References

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