Software testing and concolic execution

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Software testing

Definition

From Wikipedia: Software testing is an investigation conducted to provide stakeholders with information about the quality of the product or service under test.

Bug impact

- $100 Billion per year in Europe
- Rocket Arianne V : $370 Million
- Therac-25 (Radiotherapy) : People died...

Certifications

- **ISO/IEC 9126** : Software engineering - Product quality
- **SGS** : Certification services from SGS demonstrate that your products, processes, systems or services are compliant with national and international regulations and standards.
- **ED-12C/DO-178C** : Software Considerations in Airborne Systems and Equipment Certification

Software testing statistics

	Fast	Intelligent	Code coverage
Manual test	KO	OK	OK
Automatic test	OK	KO	KO
Formal proof	KO	OK	OK

Bugs hunting

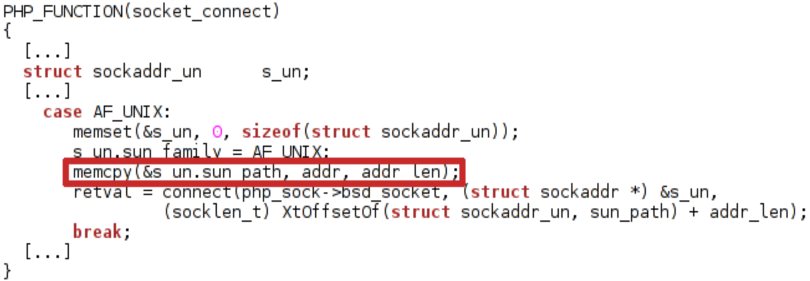
Bugs hunting

To find bugs, we have several methodologies.

- White box
- Black box
- Pattern matching
- Dumb fuzzing
- In-memory fuzzing
- ...

White box

PHP 5.3.6 - Stack buffer overflow in socket_connect (CVE-2011-1938)



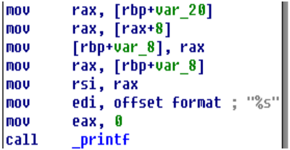
```
PHP_FUNCTION(socket_connect)
{
  [...]
  struct sockaddr_un      s_un;
  [...]
    case AF_UNIX:
      memset(&s_un, 0, sizeof(struct sockaddr_un));
      s_un.sun_family = AF_UNIX;
      memcpy(&s_un.sun_path, addr, addr_len);
      retval = connect(php_sock->bsd_socket, (struct sockaddr *) &s_un,
               (socklen_t) XtOffsetOf(struct sockaddr_un, sun_path) + addr_len);
      break;
  [...]
}
```

Black box

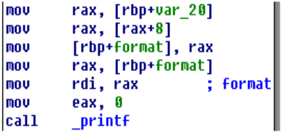
Most vulnerabilities are found in private softwares thanks to black box fuzzing

- Same idea than white box fuzzing
- Need to skill++ in assembly
- Really more time consuming than white box fuzzing

Pattern matching



```
mov     rax, [rbp+var_20]
mov     rax, [rax+8]
mov     [rbp+var_8], rax
mov     rax, [rbp+var_8]
mov     rsi, rax
mov     edi, offset format ; "%s"
mov     eax, 0
call    _printf
```



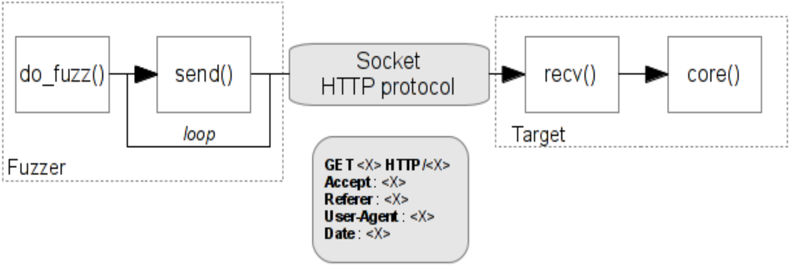
```
mov     rax, [rbp+var_20]
mov     rax, [rax+8]
mov     [rbp+format], rax
mov     rax, [rbp+format]
mov     rdi, rax        ; format
mov     eax, 0
call    _printf
```

Dumb fuzzing

The idea is to fuzz the program with semi-random data (based on a specification of the fileformat/protocol/whatever)

1. Focus a specific RFC (Ex: http, ftp, pdf, png...)
2. Send semi-random data based on the RFC's fields.

Dumb fuzzing - http server

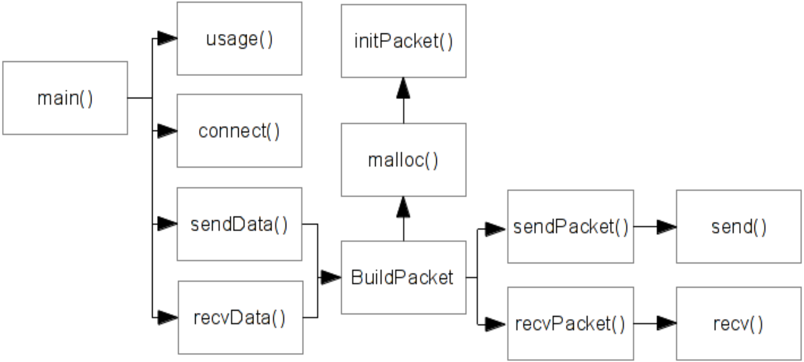


In-memory fuzzing

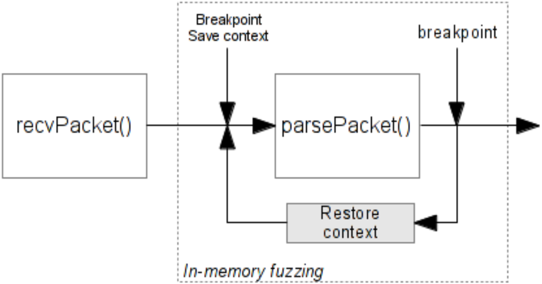
The idea of this method is to instrument directly the target application's code to fuzz it. Here are the different steps:

1. Break before and after the target function
2. Save the context execution
3. Send semi-random data
4. Restore the execution context previously saved
5. Repeat until a crash is triggered

In-memory fuzzing - Call graph



In-memory fuzzing - Concept



Manual vs automatic testing

With the classical automatic tests it's difficult to detect some bugs :

- Info leaks
- All overflows without crashs
- Design errors
- ...

Concolic execution

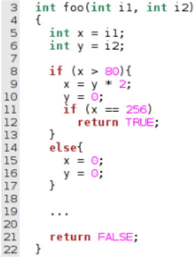
Concrete execution

The concrete execution is the execution of a real program.

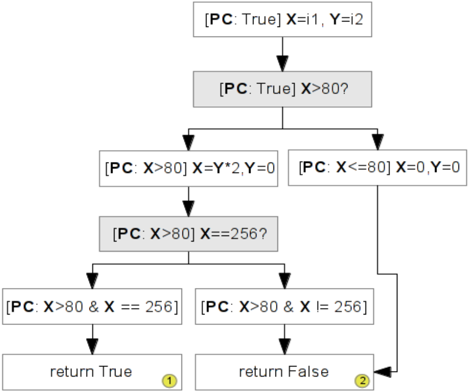
Symbolic execution

The symbolic execution is used to determine a time T all conditions necessary to take the branch or not.

Symbolic execution - Example



```
int foo(int i1, int i2)
{
  int x = i1;
  int y = i2;

  if (x > 80){
    x = y * 2;
    y = 0;
    if (x == 256)
      return TRUE;
  }
  else{
    x = 0;
    y = 0;
  }

  ...

  return FALSE;
}
```



[**PC**: True] **X**=i1, **Y**=i2

[**PC**: True] **X**>80?

[**PC**: **X**>80] **X**=**Y***2,**Y**=0

[**PC**: **X**<=80] **X**=0,**Y**=0

[**PC**: **X**>80] **X**==256?

[**PC**: **X**>80 & **X** == 256]

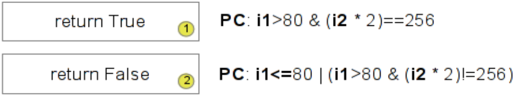
[**PC**: **X**>80 & **X** != 256]

return True ①

return False ②

Symbolic execution - Example

Three possible paths. One path for **True** and two paths for **False**.



return True ①

PC: **i1**>80 & (**i2** * 2)==256

return False ②

PC: **i1<=**80 | (**i1**>80 & (**i2** * 2)!=256)

Concolic execution

Concolic execution is a technic that uses both symbolic and concrete execution to solve a constraint path.

IR and constraints solver

Valgrind

Valgrind is an instrumentation framework for building dynamic analysis tools.

Valgrind - VEX

VEX is the Valgrind's intermediate language.

Valgrind - VEX sample

Instruction: **add eax, ebx**

```
t3 = GET:I32(0)      # get %eax, a 32-bit integer (t3 = eax)
t2 = GET:I32(12)     # get %ebx, a 32-bit integer (t2 = ebx)
t1 = Add32(t3,t2)    # t1 = addl(eax, ebx)
PUT(0) = t1          # put %eax (eax = t1)
```

Z3

Z3 is a high-performance theorem prover developed by Microsoft.

Z3 - Example

```
$ cat ./ex.py
from z3 import *

x = BitVec('x', 32)
s = Solver()
s.add((x ^ 0x55) + (3 - (2 * 12)) == 0x30)
print s.check()
print s.model()
```

```
$ ./ex.py
sat
[x = 16]
```

Z3 - Why ?

We will use it to solve all the constraints from our VEX's output.

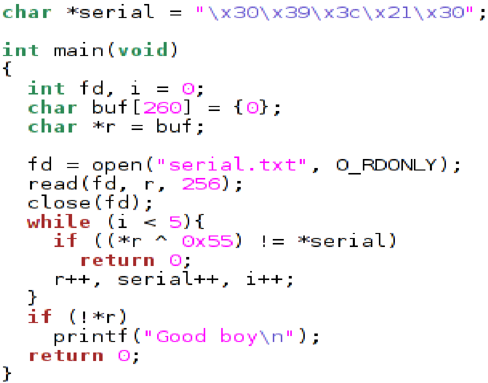
Proof of concept

PoC for fun

Last summer, with my friends **Ahmed Bougacha** and **Pierre Collet**, we worked on a concolic PoC just for fun.

Goal

Objectif : Solve this dumb crackme

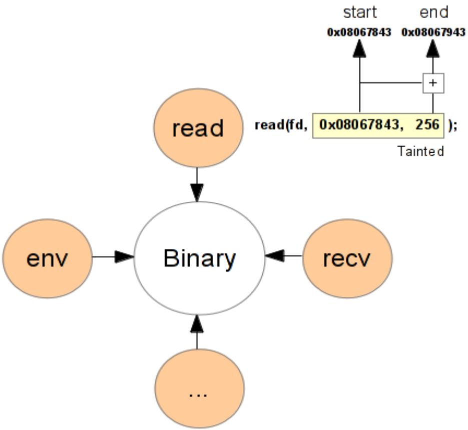


```
char *serial = "\x30\x39\x3c\x21\x30";

int main(void)
{
  int fd, i = 0;
  char buf[260] = {0};
  char *r = buf;

  fd = open("serial.txt", O_RDONLY);
  read(fd, r, 256);
  close(fd);
  while (i < 5){
    if ((*r ^ 0x55) != *serial)
      return 0;
    r++, serial++, i++;
  }
  if (!*r)
    printf("Good boy\n");
  return 0;
}
```

Plan

1. Taint the user input (via Valgrind)
2. Spread the taints (via Valgrind)
3. Save all constraints (via Valgrind)
4. Solve all constraints (via Z3)

Taint syscall entries - Diagram



Taint syscall entries - in Valgrind

With valgrind we can add a **Pre** and **Post** syscall handler.

Taint syscall entries - in Valgrind

```
static void pre_syscall(ThreadId tId, UInt syscall_number, UWord* args,
                        UInt nArgs){
}

static void post_syscall(ThreadId tId, UInt syscall_number, UWord* args,
                         UInt nArgs, SysRes res){
}

static void init(void)
{
  VG_(details_name)            ("Taminoo");
  VG_(details_version)         (NULL);
  VG_(details_description)     ("Taint analysis poc");
  [...]
  VG_(basic_tool_funcs)        (init, instrument, fini);
  [...]
  VG_(needs_syscall_wrapper)   (pre_syscall, post_syscall);
}

VG_DETERMINE_INTERFACE_VERSION(init)
```

Spread the taints

To propagate correctly the taints, we instrument each instruction of the binary. If it is a **GET**, **LOAD**, **PUT** or **STORE** instruction we spread the taints.

Spread the taints

The variable **a** is tainted. When **b = a** and **c = b**, **b** and **c** will also be tainted because they can be controlled via **a**.

```
uint32_t a, b, c;

a = atoi(user_input);
b = a; /* b is tainted */
c = b; /* c is tainted */
```

Spread the taints - in Valgrind

```
switch (st->tag) {
    case Ist_Store:
                    INSERT_DIRTY(helper_store,
                    /* dst_addr */ st->Ist.Store.addr,
                    /* src_tmp  */ INSERT_TMP_NUMBER(st->Ist.Store.data),
                    /* size     */ INSERT_EXPR_SIZE(st->Ist.Store.data));
                    break;
    case Ist_Put:
                    INSERT_DIRTY(helper_put,
                    /* dst_reg */ mkIRExpr_HWord(st->Ist.Put.offset),
                    /* src_tmp */ INSERT_TMP_NUMBER(st->Ist.Put.data),
                    /* size    */ INSERT_EXPR_SIZE(st->Ist.Put.data));
                    break;
    case Iex_Get:
                    INSERT_DIRTY(helper_get,
                    /* dst_tmp */ mkIRExpr_HWord(dst),
                    /* src_reg */ mkIRExpr_HWord(data->Iex.Get.offset),
                    /* size    */ mkIRExpr_HWord(sizeofIRType(data->Iex.Get.ty)));
                    break;
    case Iex_Load:
                    INSERT_DIRTY(helper_load,
                    /* dst_tmp  */ mkIRExpr_HWord(st->Ist.WrTmp.tmp),
                    /* src_addr */ st->Ist.WrTmp.data->Iex.Load.addr,
                    /* size     */ INSERT_TYPE_SIZE(data->Iex.Load.ty));
                    break;
    [...]
}
```

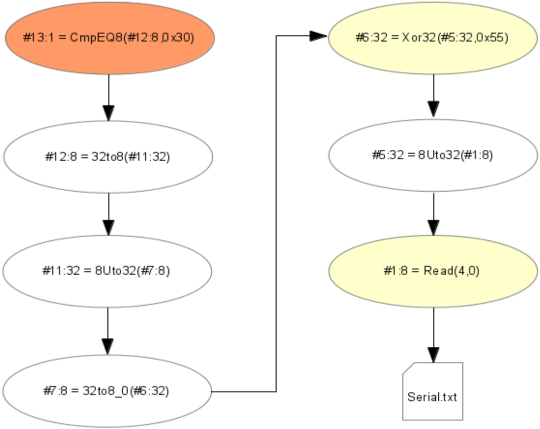
Constraints - Output

```
==14567==
#1:8          = Read(4,0)
#2:8          = Read(4,1)
#3:8          = Read(4,2)
#4:8          = Read(4,3)
#5:32         = 8Uto32(#1:8)
#6:32         = Xor32(#5:32,0x55)
#7:8          = 32to8_0(#6:32)
#8:8          = 32to8_1(#6:32)
#9:8          = 32to8_2(#6:32)
#10:8         = 32to8_3(#6:32)
#11:32        = 8Uto32(#7:8)
#12:8         = 32to8(#11:32)
#13:1         = CmpEQ8(#12:8,0x30) = False
#14:32        = 1Uto32(#13:1)
#15:1         = 32to1(#14:32)
Jump(#15:1)  = False
#6 freed
#5 freed
#14 freed
#13 freed
#12 freed
#15 freed
#11 freed
#7 freed
==14567==
```

Constraints - List

Every constraint depends of the previous constraint.

Constraints - List



Solve constraints with Z3

All the constraints are converted using the Z3 syntax

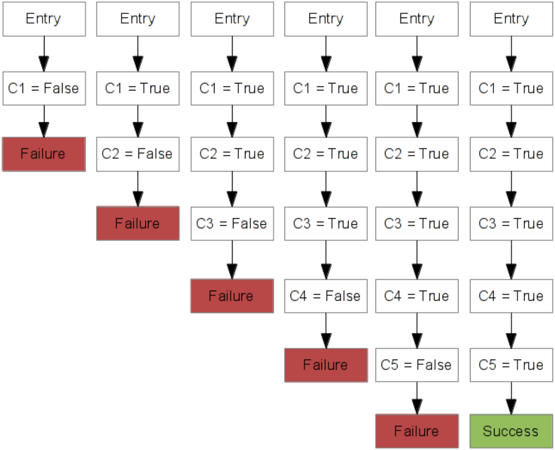
Solve constraints with Z3 - Original constraint

The first constraint is : **CmpEQ8(Xor32(Read(4,0),0x55),0x30)**

Solve constraints with Z3 - Z3 pattern

```
# First constraint in Z3 pattern
x = BitVec('x', 32)
s = Solver()
s.add((x ^ 0x55) == 0x30)
```

Solve constraints with Z3 - Concolic execution



Solve constraints with Z3 - All constraints solved

C1 = **CmpEQ8(Xor32(Read(4,0),0x55),0x30) = 'e'**

C2 = **CmpEQ8(Xor32(Read(4,1),0x55),0x39) = 'l'**

C3 = **CmpEQ8(Xor32(Read(4,2),0x55),0x3c) = 'i'**

C4 = **CmpEQ8(Xor32(Read(4,3),0x55),0x21) = 't'**

C5 = **CmpEQ8(Xor32(Read(4,4),0x55),0x30) = 'e'**

Extra

Blog post : http://shell-storm.org/blog/Concolic-execution-taint-analysis-with-valgrind-and-constraints-path-solver-with-z3/

Questions ?

Questions ?

Thanks !

http://sbxc.org

http://twitter.com/JonathanSalwan