Exploiting Software Vulnerabilities

Program Binary Analysis

Universidad Zaragoza 1542

Dept. of Computer Science and Systems Engineering
University of Zaragoza, Spain

Course 2021/2022

Master's Degree in Informatics Engineering

University of Zaragoza

Seminar A.25, Ada Byron building

Outline

Outline

Universidad Zaragoza

Introduction

```c
#include <stdio.h>

int main(int argc, char *argv[])
{
    printf("hello world!\n");
    return 0;
}
```

```asm
push    ebp
mov     ebp, esp
and     esp, -16
sub     esp, 16
call    ___main
mov     DWORD PTR [esp], OFFSET FLAT:LC0
call    _puts
mov     eax, 0
leave
ret
```

- **Programs are written in text**
  - Both source code and assembly!
  - **Character sequences (bytes)**
  - Difficult to work with (for humans, not for machines)
  - We need some **structured representation**

Universidad Zaragoza

Introduction

Program Analysis

Automatically reason and derive properties about the behavior of computer programs

Approaches

- **Static Program Analysis**
  - Without running the program
  - The abstract model of the program is obtained and (symbolically) executed
  - Analysis performed through the abstract model
  - **Examples**: CFA, DFA, concolic execution, ...
- **Dynamic Program Analysis**
  - Running the program on some chosen inputs
  - Traces are collected and then analyzed
  - Analysis performed through these concrete executions
  - **Examples**: software testing, taint analysis, ...

Introduction

Input program formats for analysis

- **Abstract model**: all unnecessary information for analysis have been removed. Only the necessary information remains
- **Source code**: Keep track of high-level, human-readable information about the program (variables, types, functions, etc.)
- **Bytecode**: may vary depending on the bytecode considered, but keep a record of little high-level information about the program, such as types and functions. The programs are unstructured
- **Binary file**: just keep track of statements in an unstructured way (no for-loop, no clear argument passing in procedures, etc). No type, no names. The binary file can include meta-data that can be useful for analysis (symbols, debug, etc.)
- **Memory dump**: Pure assembler instructions with a full memory state of the current execution. We no longer have the meta-data of the executable file

Binary code is the closest format of what will be executed!

Introduction

Binary code vs. source code

What you code is not what you execute!

We want to analyze binary code. It can come as:

- an executable file,
- an object file,
- a dynamic library,
- a firmware,
- a memory dump,
- ...

We do not trust to obtain the corresponding high-level source code

Universidad Zaragoza

Introduction

Motivations

Why should we analyze binary programs?

- Lack of high-level source code
- Low-level assembly code embedded in source code
- Legacy code
- Commercial Off-the-shelf software (COTS)
- App stores (for mobile phones and tablets)
- Malware (or other “hostile” programs)
- Technology forecast
- Mistrust in the compilation chain
- C compiler possibly buggy
- Checking for low-level bugs (e.g., exploiting a stack buffer overflow)
- Errors with strong hardware interconnection

Introduction

Understanding papers on Program Analysis

> *For those who keep track of such things, checkers in the research system typically traverse program paths (flow-sensitive) in a forward direction, going across function calls (inter-procedural) while keeping track of call-site-specific information (context-sensitive) and toward the end of the effort had some of the support needed to detect when a path was infeasible (path-sensitive).*

Note these terms

- **Flow-(in)sensitive**
- **Inter-(intro)procedural**
- **Context-(in)sensitive**
- **Path-(in)sensitive**

Further reading: *A few billion lines of code later: using static analysis to find bugs in the real world.* Al Bessey, Ken Block, Ben Chelf, Andy Chou, Bryan Fulton, Seth Hallem, Charles Henri-Gros, Asya Kamsky, Scott McPeak, Dawson Engler. *Communications of the ACM*, vol. 53, iss. 2, pp. 66-75 (February 2010). doi: 10.1145/1646353.1646374

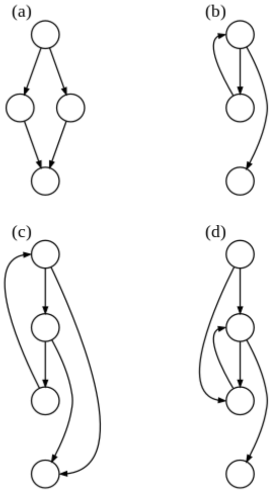
Universidad Zaragoza

Outline

1. Introduction to Program Binary Analysis
2. Static Analysis Techniques
3. Dynamic Analysis Techniques

Universidad Zaragoza

Static Analysis Techniques
Control-Flow Graphs



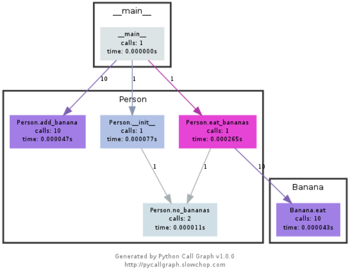
- **Control flow within a function**
- **Nodes: basic blocks**
  - Sequence of consecutive program instructions that have an entry point (first executed instruction) and an exit point (last executed instruction)
  - Entry and exit blocks
- **Edge**: control flows from A to B

Applications

- Compiler optimizations
- Data-flow analysis (taint analysis)
- Behavioral-based monitors

Credits: `https://en.wikipedia.org/wiki/Control_flow_graph`

Static Analysis Techniques
Call Graphs

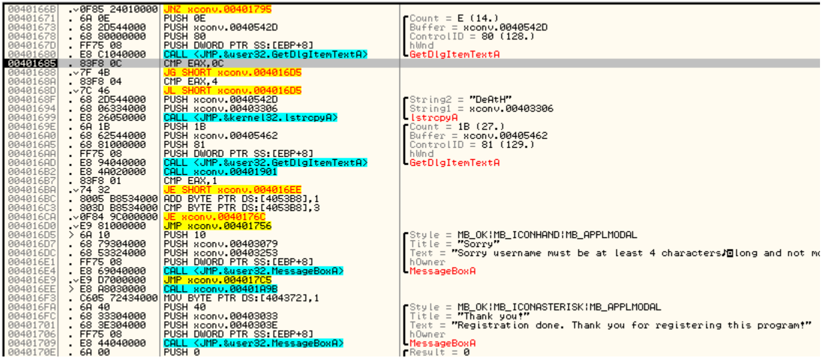


- **Interprocedural CFG**. **Information flow between functions**
- **Nodes**: functions
- **Edge**: A could call B
- Types: static, dynamic (record of program execution)
- Application: find never called procedures
- **Tools available for automatic generation of call graphs**

Credits: `https://en.wikipedia.org/wiki/Call_graph`

Static Analysis Techniques

Disassembling



- Roughly speaking, **read `PUSH EAX` instead of `0x50`**
- **Many tools** see `https://en.wikibooks.org/wiki/X86_Disassembly/Disassemblers_and_Decompilers`
  - Win32Dasm
  - OllyDBG (it is also a debugger)
  - IDA Pro (it is also a debugger)
  - r2 (it is also a debugger)

Universidad Zaragoza

Static Analysis Techniques
Disassembling

Main challenges

- **Variable-length instruction sets**: overlapping instructions
- **Mixed data and code**: misclassify data as instructions
- **Indirect jumps**: any location could be the beginning of an instruction!
- **Start of functions**: when calls are indirect
- **End of functions**: when there is no dedicated return instruction
  - Handwritten assembly code may not meet standard call conventions
- **Code compression**: the code of two functions overlaps
- **Self-modifying code**

Universidad Zaragoza

Static Analysis Techniques

Decompilation – example

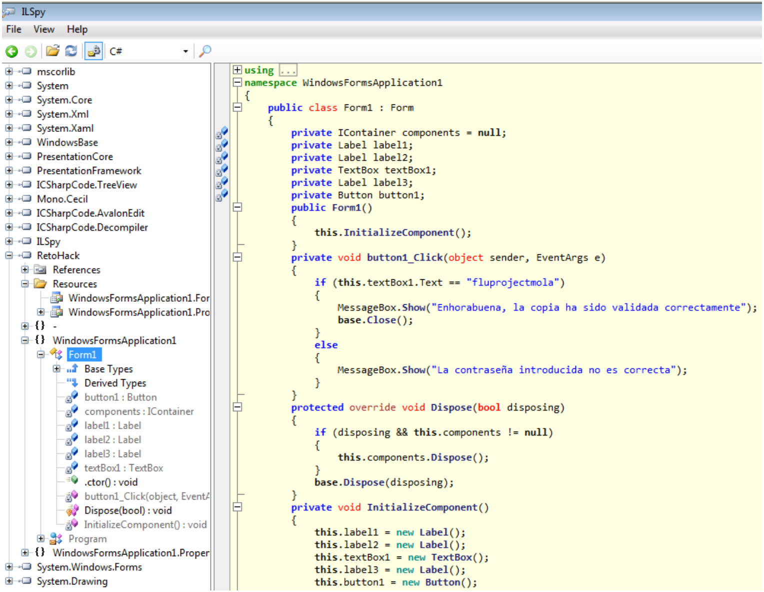
```
int __stdcall sub_40162C(HWND hDlg, int a2, int a3, int a4){
  HICON v4; // eax@2
  UINT v5; // eax@5

  switch ( a2 )  {
    case 272:
      v4 = LoadIconA(hInstance, (LPCSTR)0x64);
      SendMessageA(hDlg, 0x80u, 1u, (LPARAM)v4);
      break;
    case 273:
      if ( a3 == 126 ) {
        v5 = GetDlgItemTextA(hDlg, 128, dword_40542D, 14);
        if ( (signed int)v5 > 12 || (signed int)v5 < 4 ) {
          MessageBoxA(hDlg,"Sorry username must be at least 4
characters\r\nlong
and not more than 12 characters.", "Sorry", 0x10u);
        } else {
          lstrcpyA(dword_403306, dword_40542D);
          GetDlgItemTextA(hDlg, 129, byte_405462, 27);
          if ( sub_401901() == 1 ) {
            sub_401A9B();
            byte_404372 = 1;
            MessageBoxA(hDlg, "Registration done. Thank you for registering
this
program!", "Thank you!", 0x40u);
            EndDialog(hDlg, 0);
            EnableWindow(dword_403363, 0);
            SetWindowTextA(
              dword_4054A7,
              "X-Convertor v1.0  2005 by TDC and BoR0\r\n\n
Coded by\t: TDC and BoR0\r\nVersion\t\t: 1.0\r\nRelease
date\t: 18-08-2005\r\n \r\nX-Convertor converts up to 4KB
each convert.\r\n \r\nRegistered version. Thank you.\r\n");
            lstrcatA(byte_403330, dword_403306);
            SetWindowTextA(dword_4054AB, byte_403330);
          }
          else {
           ++byte_4053B8;
           if ( byte_4053B8 == 3 ) {
             MessageBoxA(hDlg, "Your serial is not correct",
                                 "Sorry", 0x10u);
             byte_4053B8 = 0;
             EndDialog(hDlg, 0);
           } else {
             MessageBoxA(hDlg, "Your serial is not correct",
                                  "Sorry", 0x10u);
           }
          }
        }
      } else {
        if ( a3 == 127 ) {
          byte_4053B8 = 0;
          EndDialog(hDlg, 0);
        }
      }
      break;
    case 16:
      byte_4053B8 = 0;
      EndDialog(hDlg, 0);
      break;
  }
  return 0;
}
```

Universidad Zaragoza

Static Analysis Techniques

Decompilation



Universidad Zaragoza

Static Analysis Techniques

Decompilation

Main challenges

- **Disassembly**: **first step of any decompiler!**
- **Target language**: the assembly code may not correspond to any source code
- **Library functions**
- **Instruction compiler-dependent equivalents**
  - `int a= 0` → `mov eax, [a]; xor eax, eax`
- **Target architecture artifacts**: unnecessary jumps-to-jumps
- **Structured control-flow**
- **Compiler optimizations**: unrolling loops, shifts, adds, ...
- **Loads/stores**: operations on arrays, records, pointers, and objects
- **Self-modification code**: typically, the segment code should be unchanged, although there are programs that modify themselves!

Static Analysis Techniques
Data Flow Analysis

- Analyze the **effect of each basic block**
- Compose basic block effects to derive information at the limits of the basic blocks
- Framework for **providing facts about programs.** Based on all paths through the program (including infeasible paths as well)
- **Derive information about the dynamic behavior of a program by examining only the code statically**

Useful for. . .

- **Program debugging**: what definitions (of variables) can reach a program point?
- **Program optimizations**: constant folding, copy propagation, elimination of common subexpressions, etc.

Static Analysis Techniques

Data Flow Analysis

Consider the statement $a = b + c$

Statement effects

- **Uses variables** (b, c)
- **“Kills” a previous definition** (old value of a)
- **New definition** (a)

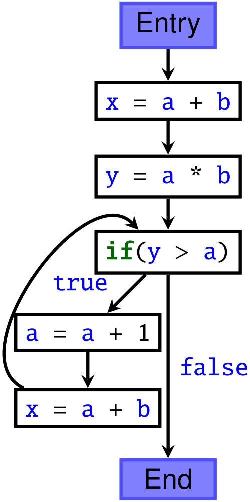
- **Compose effect of statements → effect of a basic block**
  - *Locally exposed usage*: usage of a data item that is not preceded in the basic block by a data item definition
  - Any definition of a data item removes (*kills*) all definitions of the same data item that reach the basic block
  - *Locally available definition*: last definition of the data item in the basic block

Universidad Zaragoza

Static Analysis Techniques

Data Flow Analysis

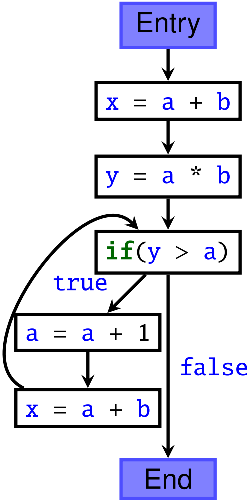
- **Facts**
  - $a + b$ is available
  - $a * b$ is available
  - $a + 1$ is available
- Let's calculate the facts that hold for each program point!



Universidad Zaragoza

Static Analysis Techniques
Data Flow Analysis

Statement	Gen	Kill
`x = a + b`	$a + b$	
`y = a * b`	$a * b$	
`y > a`		
`a = a + 1`		$a + b$
		$a * b$
	$a + 1$	



Static Analysis Techniques

Data Flow Analysis

- *Forward* versus *backward*: data flow from the inside out (vs outside in)
- *Must* versus *may*: at joint points, just keep the facts that hold on all paths (vs. any path) that are joined

	Must	**May**
Forward	Available expressions	Reaching definitions
Backward	Very busy expressions	Live variables

Limitations

- **Data-Flow Analysis is good for analyzing local variables**
  - **What happens to values stored in the heap?**
  - Not modeled on traditional data flow
- Suppose `*x = p`
  - *Assume all data flow facts are killed*
  - Or assume writing via `x` can affect any variable whose address has been taken
- In general, **it is difficult to analyze pointers**

Universidad Zaragoza

Static Analysis Techniques

Symbolic Execution

- **Allows us to scale and model all the possible executions of a program**
- Concrete versus symbolic execution
  - **Tests work, but each test only explores one possible execution path**
- **Symbolic execution generalizes testing**
  - Allows unknown symbolic variables in evaluation
  - **Checks the feasibility of the program paths**

Main challenges

- **Path explosion**
- **Modeling statements and environments**
- **Constraint resolution**

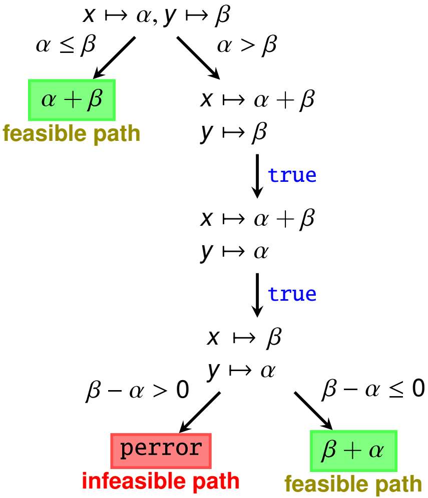
Further reading: Roberto Baldoni, Emilio Coppa, Daniele Cono D'elia, Camil Demetrescu, and Irene Finocchi. *A Survey of Symbolic Execution Techniques*. ACM Comput. Surv. 51, 3, Article 50 (July 2018), 39 pages. doi: 10.1145/3182657

Static Analysis Techniques

Symbolic Execution

```c
int f(int x, int y)
{
    if(x > y)
    {
        x = x + y;
        y = x - y;
        x = x - y;
        if(x - y > 0)
            perror("Error!");
    }

    return x + y;
}
```



How to decide which branches are feasible?

Combine the path condition with the branch condition and ask an SMT solver!

Static Analysis Techniques

Symbolic Execution – example: bug finding

Catch the error! What value triggers it?

```
int bar(int i)
{
    int j = 2*i;
    i++;
    i = i*j;
    if (i < 1)
        i = -i;

    i = j/i;
    return i;
}
```

False branch condition

$i = (i_{in} + 1)2i_{in}$

$(i_{in} + 1)2i_{in} \geq 1$

True branch condition

$i = -(i_{in} + 1)2i_{in}$

$(i_{in} + 1)2i_{in} < 1$

Static Analysis Techniques

Symbolic Execution – example: bug finding

Catch the error! What value triggers it?

```c
int bar(int i)
{
    int j = 2*i;
    i++;
    i = i*j;
    if (i < 1)
        i = -i;

    i = j/i;
    return i;
}
```

False branch condition

$$i = (i_{in} + 1)2i_{in}$$
$$(i_{in} + 1)2i_{in} \geq 1$$

True branch condition

$$i = -(i_{in} + 1)2i_{in}$$
$$(i_{in} + 1)2i_{in} < 1$$

Division by zero creates problems. . .

Static Analysis Techniques

Symbolic Execution – example: bug finding

Catch the error! What value triggers it?

```
int bar(int i)
{
    int j = 2*i;
    i++;
    i = i*j;
    if (i < 1)
        i = -i;

    i = j/i;
    return i;
}
```

False branch condition $i = (i_{in} + 1)2i_{in}$

$(i_{in} + 1)2i_{in} \geq 1$

True branch condition $i = -(i_{in} + 1)2i_{in}$

$(i_{in} + 1)2i_{in} < 1$

Division by zero creates problems...

False branch is always safe

$(i > 0, \forall i_{in} | (i_{in} + 1)2i_{in} \geq 1)$

What about the true branch?

Static Analysis Techniques

Symbolic Execution – example: bug finding

Catch the error! What value triggers it?

```
int bar(int i)
{
    int j = 2*i;
    i++;
    i = i*j;
    if (i < 1)
        i = -i;

    i = j/i;
    return i;
}
```

False branch condition	$i = (i_{in} + 1)2i_{in}$ $(i_{in} + 1)2i_{in} \geq 1$
True branch condition	$i = -(i_{in} + 1)2i_{in}$ $(i_{in} + 1)2i_{in} < 1$

Division by zero creates problems...
False branch is always safe
$(i > 0, \forall i_{in} | (i_{in} + 1)2i_{in} \geq 1)$
What about the true branch?
$-(i_{in} + 1)2i_{in} = 0$

Static Analysis Techniques

Symbolic Execution – example: bug finding

Catch the error! What value triggers it?

```
int bar(int i)
{
    int j = 2*i;
    i++;
    i = i*j;
    if (i < 1)
        i = -i;

    i = j/i;
    return i;
}
```

False branch condition	$i = (i_{in} + 1)2i_{in}$ $(i_{in} + 1)2i_{in} \geq 1$
True branch condition	$i = -(i_{in} + 1)2i_{in}$ $(i_{in} + 1)2i_{in} < 1$

Division by zero creates problems...
False branch is always safe
$(i > 0, \forall i_{in} | (i_{in} + 1)2i_{in} \geq 1)$
What about the true branch?
$-(i_{in} + 1)2i_{in} = 0 \rightarrow i_{in} = -1, i_{in} = 0$

Static Analysis Techniques

Symbolic Execution – example: class exercise

Which values of `a` and `b` make the `assert` fail?

```
void foo(int a, int b)
{
    int x = 1, y = 0;
    if (a != 0){
        y = 3 + x;
        if (b == 0)
            x = 2*(a + b);
    }
    assert(x - y != 0);
}
```

State 1

$\sigma = \{a \mapsto \alpha, b \mapsto \beta\}$

$\pi = \mathit{true}$

`int x = 1, y = 0`

Universidad Zaragoza

Static Analysis Techniques

Symbolic Execution – example: class exercise

Which values of `a` and `b` make the `assert` fail?

```
void foo(int a, int b)
{
    int x = 1, y = 0;
    if (a != 0){
        y = 3 + x;
        if (b == 0)
            x = 2*(a + b);
    }
    assert(x - y != 0);
}
```

State 1

$\sigma = \{a \mapsto \alpha, b \mapsto \beta\}$

$\pi = true$

`int x = 1, y = 0`

↓

State 2

$\sigma = \{a \mapsto \alpha, b \mapsto \beta, x \mapsto 1, y \mapsto 0\}$

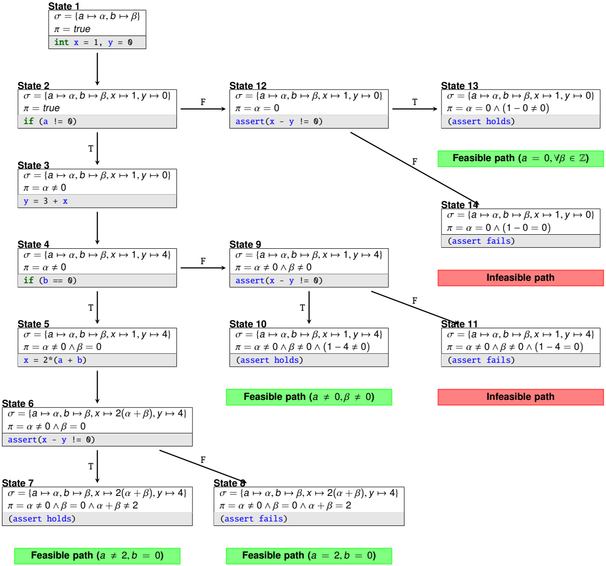
$\pi = true$

`if (a != 0)`

(you can continue it. . .)

Static Analysis Techniques

Symbolic Execution – solution to the class exercise above



Universidad Zaragoza

Outline

Dynamic Analysis Techniques

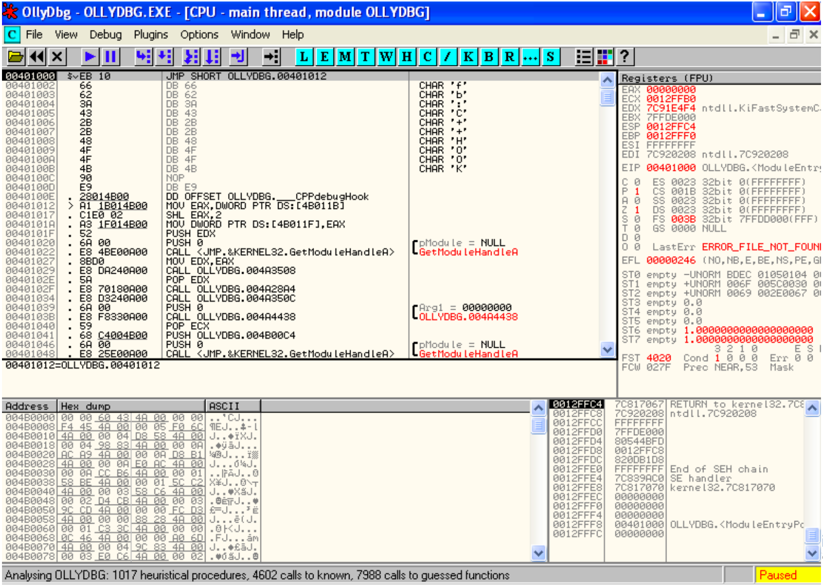
Debugging

- **Run the program instructions with special software**: *debuggers*
  - We can see the values of each CPU register, stack, memory, etc.
- Source code vs. binary debugging
- **Breakpoints**: stops execution when reached
  - Software (memory) breakpoints
  - Hardware breakpoints
  - In run, read, or write operations
- Step into / step onto

Universidad Zaragoza

Dynamic Analysis Techniques

Debugging (example: `OllyDBG`)



Dynamic Analysis Techniques
Fuzzing

Roughly speaking, "fuzzing means…" (quoting Iñaki Rodríguez-Gastón)

Dynamic Analysis Techniques
Fuzzing

Roughly speaking, "fuzzing means…" (quoting Iñaki Rodríguez-Gastón)

- **Form of vulnerability analysis in application programs**
- **Black-box approach** (at the beginning): no prior knowledge of the internal aspects of the program
  - **Evolved to a white-box approach**: state-of-the-art fuzzers "learn" from program behavior
- **The application is given many anomalous (unexpected, invalid, or random data) inputs**
- **The application is monitored for any signs of error**
  - Unexpected behavior
  - Crashes
    - Buffer overflow
    - Integer overflow
    - Memory corruption errors
    - Format string bugs

Universidad Zaragoza

Dynamic Analysis Techniques
Fuzzing

Charlie Miller's "five lines of Python" dumb fuzzer

- **Found vulnerabilities in PDF readers and MS Powerpoint**

```
numwrites = random.randrange(math.ceil((float(len (buf)) / FuzzFactor))) + 1
for j in range (numwrites):
     rbyte = random.randrange(256)
     rn = random.randrange(len(buf))
     buf[rn] = "%c"%(rbyte);
```

A simple example: HTTP GET requests

- **Standard HTTP GET request**
  - GET /index.html HTTP/1.1
- **Anomalous requests**
  - AAAAAA. . . AAAA /index.html HTTP/1.1
  - GET ///////index.html HTTP/1.1
  - GET %n%n%n%n%n%n.html HTTP/1.1
  - GET /AAAAAAAAAAAAA.html HTTP/1.1
  - GET /index.html HTTTTTTTTTTTTTP/1.1
  - GET /index.html HTTP/1.1.1.1.1.1.1.1
  - etc.

Types of fuzzers

- **Mutation-based fuzzing**
- **Generation-based fuzzing**

Dynamic Analysis Techniques

Taint analysis

Can you measure the influence of the input data on the application?

- Data comes from tainted sources (any external input) and ends up in tainted sinks
- *Flow* from X to Y: **an operation that uses X to derive a value Y**
- **Tainted value: if the source of the value X is untrustworthy** (e.g., user-supplied string)

Taint Propagation

- **Object X tainted the object Y**
- **Taint operator** t: $X \mapsto t(Y)$
- **The taint operator is transitive**
  - $X \mapsto t(Y)$ and $Y \mapsto t(Z)$, then $X \mapsto t(Z)$

Dynamic Analysis Techniques

Taint analysis

Main challenges

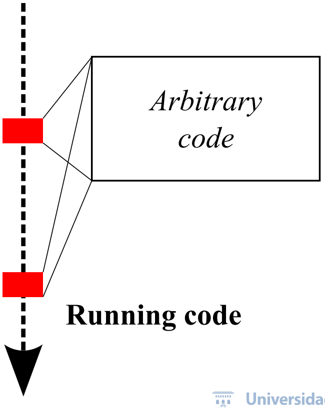
- **Tainted addresses**
  - Distinguishing between memory addresses and cells is not always appropriate
  - Taint granularity is important (bit, byte, word, etc.)
- **Undertainting**
  - Dynamic taint analysis does not adequately handle some types of information flow
- **Overtainting**
  - Deciding when to introduce a taint is often easier than deciding when to remove it
- **Detection time vs. attack time**
  - When used for attack detection, dynamic taint analysis may generate an alert too late

Dynamic Analysis Techniques

Dynamic Binary Instrumentation

adding arbitrary code during the execution of a binary

- What insert? → **instrumentation function**
- Where? → **add places**

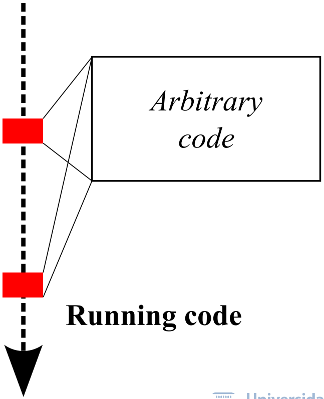


Dynamic Analysis Techniques

Dynamic Binary Instrumentation

adding arbitrary code during the execution of a binary

- What insert? → **instrumentation function**
- Where? → **add places**



Advantages

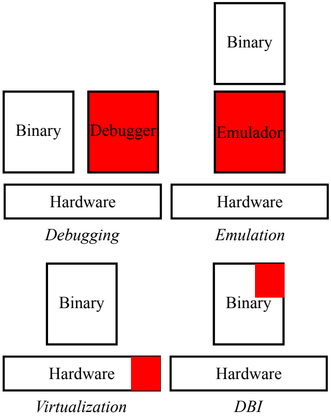
- **No need to recompile/relink every time**
- **Allow to find *on-the-fly* code**
- **Dynamically generated code**
- **Allow to instrument a process already running** (*attach*)

Main disadvantage

- **Overhead ⇒⇓ performance**

Dynamic Analysis Techniques

Placing DBI in the context of dynamic analysis



- **Executable transformation**
- **Full control over execution**
- **No architectural support needed**

Credits: J-Y. Marion, D. Reynaud *Dynamic Binary Instrumentation for Deobfuscation and Unpacking*. *DeepSec*, 2009

Exploiting Software Vulnerabilities

Program Binary Analysis

Dept. of Computer Science and Systems Engineering
University of Zaragoza, Spain

Course 2021/2022

Master's Degree in Informatics Engineering

University of Zaragoza

Seminar A.25, Ada Byron building