Dynamic Program Analysis and Software Exploitation

From the crash to the exploit code

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Agenda

- Objectives
- History
- Introduction
- Concepts of Taint Analysis
  - Taint Sources
  - Intermediate Languages and Tainted Sources
  - Explosion of Watched Data
- Backward Taint Analysis
  - From the crash to the exploit code
- Existent solutions and comparisions
- Future

Objectives

- Explain my latest Phrack Article
- Demonstrate how vulnerability finding works (or is supposed to work)
- Give some concepts about program analysis for vulnerability exploitation
- Explain the challenges the exploit writer faces nowadays
- Be fun?

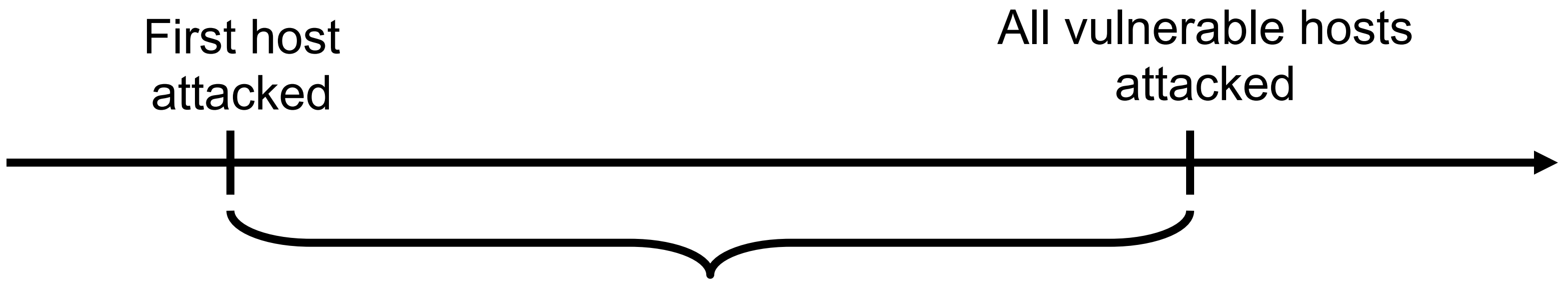
Security nowadays (yeap, again the same slides)

- Buggy programs deployed on critical servers
- Rapidly-evolving threats, attackers and tools (exploitation frameworks)
- Lack of developers training, resources and people to fix problems and create safe code
- **That's why we are here today, right?**

Sorry, really sorry

- Usually I start from the end and here I was supposed to show an 0day vulnerability in Excel
- Everything is ready to be presented using the tool that I'll explain in the presentation
- The problem: Microsoft did not issue the patch yet -> Well, they delayed it (it was supposed to be released in March, now only in April)
  - I'm not blaming Microsoft, they've been very supportive

Security nowadays – 0day challenge



Reaction time

Slammer: 10 mins

Future worms: < 1 minute [Staniford et. al. 2002]

<u>“0day Statistics</u>
Average 0day lifetime:
348 days
Shortest life:
99 days
Longest life:
1080 (3 years)"

\- Justine Aitel

History

- Original Motivation: Complex client-side vulnerability in a closed (at the time) file format
- Extended Motivation: Trying to better analyse hundred thousands of bugs in word (search for Ben Nagy, Coseinc)
- Initial version integrated with a fuzzer, only for Linux (showed past year here in Troopers)
- Ported version for Solaris to analyze a vulnerability released by Secunia in the same software RISE Security released a vulnerability some time before
- Thanks to Julio Auto parallel research in the same field, we created together the WinDBG version presented here

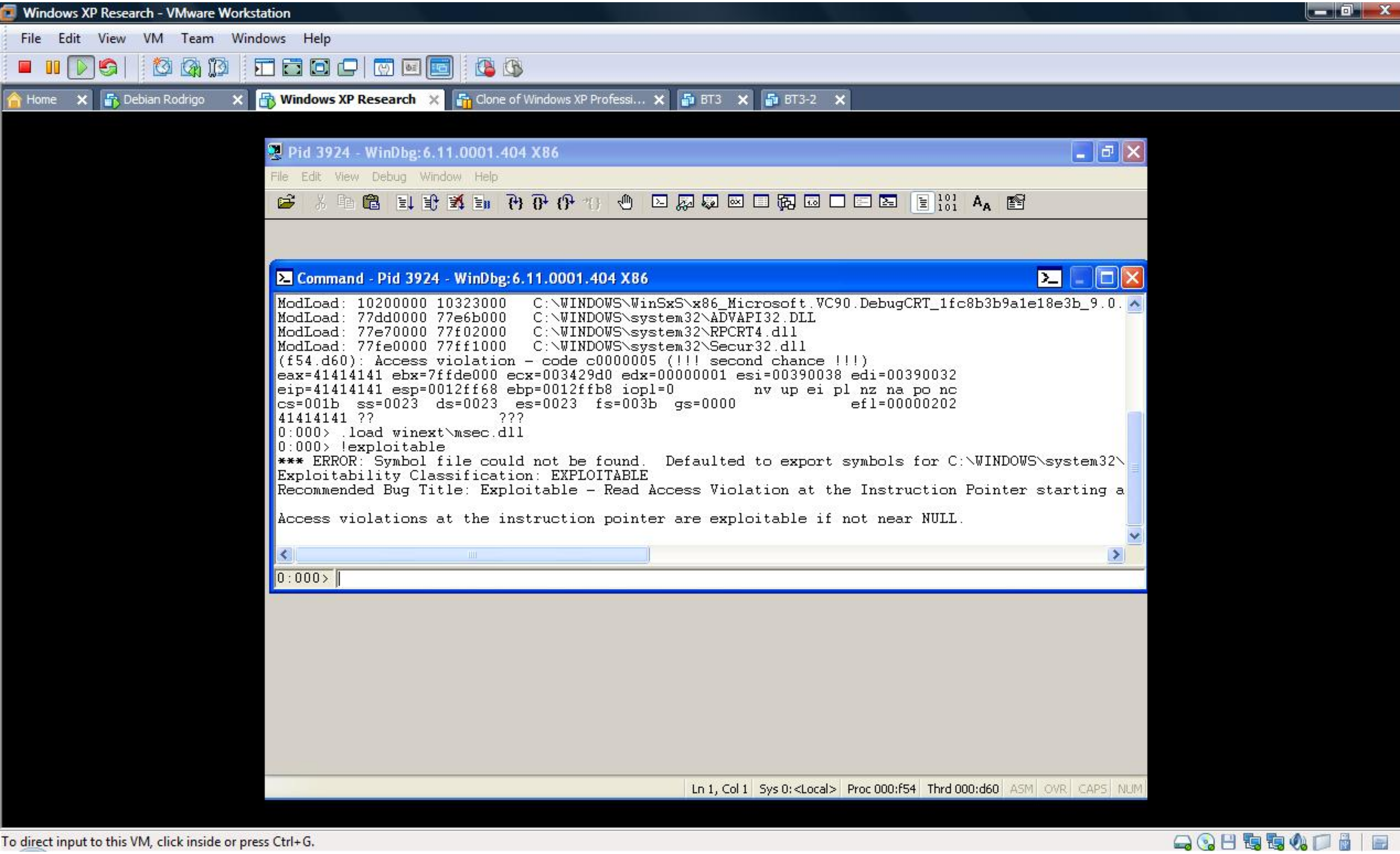
Introduction – What is program analysis for us?

- Make a computational system reason automatically (or at least with little human assistance) about the behaviour of a program and draw conclusions that are somehow useful

- Help us to determine exploitability of vulnerabilities, or to rapidly develop an exploit code

- The most widely known solution for the exploitability determination is given by Microsoft: !exploitable

!exploitable



!exploitable

- This is incorrectly classified as EXPLOITABLE because the tool always assume that the attacker has control over all the input operands
- In this presentation, we are going to try to answer the question: Are the input operands in the attacker’s control?

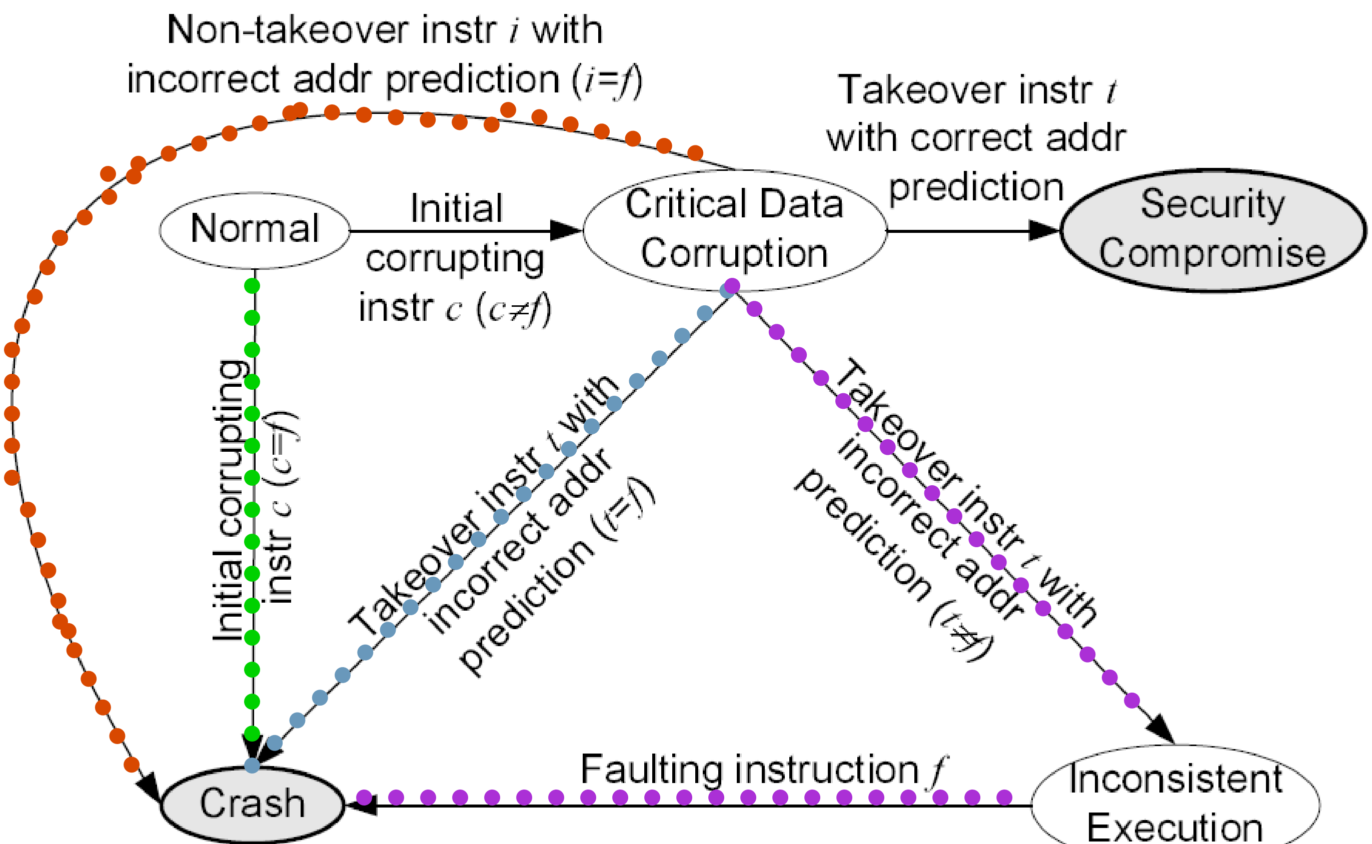
Concepts of Taint Analysis

- Taint Analysis is one kind of program flow analysis and we use it to define the influence of external data (attacker's controlled data) over the analyzed application

- Since the information flows, or is copied to, or influence other data there is a need to follow this influence in order to determine the control over specific areas (registers, memory locations). This is a requirement for determine exploitability

State Transition for Memory Corruption

- Case 1 (green): Format String
- Case 2 and 3 (red and blue): buffer overflow
- Case 4 (purple): unpredictable



c: corrupting instruction
t: takeover instruction
f: faulting instruction

Source:
Automatic Diagnosis and Response to Memory Corruption Vulnerabilities

So, what?

- Legitimate assumption:
  - To change the execution of a program illegitimately we need to have a value being derived from the attacker's input (which we call: controlled by the attacker)

- String sizes and format strings should usually be supplied by the code itself, not from external, un-trusted inputs.

- Any data originated from or arithmetically derived from un-trusted source must be inspected.

Taint Analysis

- Tainted data: Data from un-trusted source
- Keep track of tainted data (from un-trusted source)
- Monitors program execution to track how tainted attribute propagates
- Detect when tainted data is used in sensitive way

Taint Propagation

- When a tainted location is used in such a way that a value of other data is derived from the tainted data (like in mathematical operations, move instructions and others) we mark the other location as tainted as well

- The transitive relation is:
  - If information A is used to derive information B:
    - » A->t(B) -> Direct flow
  - If B is used to derive information C:
    - » B->t(C) -> Direct flow
    - » Thus: A->t(C) -> Indirect flow

- Due to the transitive nature, you can analyze individual transitions or the whole block (A->t(C))

Location

- A location is defined as:
  - Memory address and size
  - Register name (we use the register entirely, not partially -> thus %al and %eax are the same)
    - » When setting a register, I set it higher (setting %al as tainted will also taint %eax)
    - » When clearing a register, I clear it lower

- To keep track over bit operations in a register it is important to taint the code-block level of a control flow graph
  - This create extra complexity due to the existence of the flow graph and data flow dependencies graph
  - The dependencies graph represents the influence of a source data in the operation been performed

Taint Sources

- Any information in the control of the attacker is tainted (remember the transitive relation of the tainted data)
- The more tainted information, the bigger the propagation and the required resources in order to keep track of that
- Tainted data is only deleted when it receives an assignment from an untainted source or an assignment from a tainted source resulting in a constant value not controlled by the attacker

Flows

- Explicit flow:
  - mov %eax, A
- Implicit flow:
  - If (x == 1) y=0;
- Conditional statements require a special analysis approach:
  - In our case, we are analyzing the trace of a program (not the program itself, but only what was executed during the section that generated the crash)
  - We have two different analysis step: tracing and analysis

Special Situations

- Partial Tainting: When the untrusted source does not completely control the tainted data
- Tainting Merge: When there are two different untrusted sources being used to derive some data

- Data
  – In Use: when it is referenced by an operation
  – Defined: when the data is modified

Inheritance problems

Problem: state explosion for binary operations !

Application	Propagation Tracking	Inheritance Tracking
`mov %eax ← A` `mov B ← %eax`	*taint(%eax) = taint(A)* *taint(B) = taint(%eax)*	%eax inherits from A B inherits from %eax
`add %ebx ← D`	*taint(%ebx) |= taint(D)*	insert D into %ebx's inherit-from list

Events

Rare
e.g., malloc/free, system calls

Frequent
e.g., memory access,
data movement

Tracking Instructions

- Pure assignments: Easy to track
  - If a tainted location is used to define another location, this new location will be tainted
- Operations over strings are tainted when:
  - They are used to calculate string sizes using a tained location
    - a = strlen(tainted(string));
    - Since the ‘string’ is tainted, I assume the attacker controls ‘a’
  - Search for some specific char using a tainted location, defining a flag if found or not found
    - pointer = strchr(tainted(string), some_char);
    - If (pointer) flag=1;
    - ‘flag’ is tainted if the attacker controls ‘string’ or ‘some_char’

Tracking Instructions

- Arithmetic instructions with at least one tainted data usually define tainted results
- Those arithmetic instructions can be simplified to map to boolean operations and then the following rules applies

OR truth table

XOR truth table

X	Y	X or Y
0	0	0
0	1	1
1	0	1
1	1	0

Arithmetics with Tainted Data

- OR Operand
  - If the untainted data is 1, the result is untainted
  - If the untainted data is 0, the result is tainted
- AND Operand
  - If the untainted data is 0, the result is untainted
  - If the untainted data is 1, the result is tainted
- XOR Operand
  - If it is an xor against itself, the result is untainted
  - Otherwise, the result is tainted

Eflags and Flow Information

- The eflags register can also be tainted to monitor flags conditions influencing in operations (and flow)

- In the presented approach, conditional branches are taken care due to the trace generated by the WinDBG plugin (single-stepping)

Backward Taint Analysis

- Divide the analysis process in two parts:
  - A trace from a good state to the crash (incrementally dumped to a file) -> Gather substantial information about the target application when it receives the input data, which is formally named 'analysis'
  - Analysis of the trace file -> Formally defined as 'verification' step, where the conclusive analysis is done

The need for intermediate languages...

- Assembly instructions have explicit operands, which are easy to deal with, and sometimes implicit operands:
  - Instruction: push eax
  - Explicit operand: eax
  - What it really does?
    - » ESP = ESP – 4 (a substraction)
    - » SS:[ESP] = EAX (a move)
    - » Here we have ESP and SS as implicit operands

        - Tks to Edgar Barbosa for this great example!

The tracing step

- Instead of using an intermediate language, I play straight with the debugger interfaces (WinDBG)

- The tracer stores some useful information, like effective addresses and data values and also simplifies the instructions for easy parsing:

  - CMPXCHG r/m32, r32 -> 'Compare EAX with r/m32. If equal, ZF is set and r32 is loaded into r/m32. Else, clear ZF and load r/m32 into AL'
    - » Such an instruction creates the need for conditional taints, since by controlling %eax and r32 the attacker controls r/m32 too.

Tracing File

- Contains:
  - Mnemonic of the instruction
  - Operands
  - Dependences for the source operand
    - Eg: Elements of an indirectly addressed memory
    - This creates a tree of the dataflow, with a root in the crash instruction
- The verification step reads this file and:
  - Search this tree using a BFS algorithm

Theorical Example

- 1-) mov edi, 0x1234 ; dst=edi, src=0x1234
- 2-) mov eax, [0xABCD] ; dst=eax, src=ptr 0xABCD ; Note 0xABCD is evil addr
- 3-) lea ebx, [eax+ecx*8] ; dst=ebx, src=eax, srcdep1=ecx
- 4-) mov [edi], ebx ; dst=ptr 0x1234, src=ebx
- 5-) mov esi, [edi] ; dst=esi, src=ptr 0x1234, srcdep1=edi
- 6-) mov edx, [esi] ; Crash!!!

Theorical Example – The Tree

- 6-) Where does [esi] come from?
- 5-) [edi] is moved to esi, where edi comes from and what does exist in [edi]?
- 4-) [edi] receives ebx and edi is defined in 1-) from a fixed value
- 3-) ebx comes from a lea instruction that uses eax and ecx
- 2-) eax receives a value controlled by the attacker
- ... ecx is out of the scope here :)

Limitation of the approach

- Since I only use the trace information, if the crash input data does not force a flow, I can't see the influence of the input over this specific flow data
- To solve that:
  - If a jmp is dependent of a flag, the attacker controls branch decision
  - Control over a branch means tainted EIP
  - To define the value of EIP, consider:
    - » The address if the jump is taken
    - » The address of the next instruction (if the jump is not taken)
    - » The value of the interesting flag register (0 or 1)
    - » Then: %eip <- (address of the next instruction) + value of the register flag * (|address if jump is taken – address of the next instruction|)

Existent Solutions and Comparisions

- !exploitable
  - Tries to classify unique issues (crashes appearing through different code paths, machines involved in testing, and in multiple test cases)
  - Quickly prioritizes issues (since crashes appear in thousands, while analysis capabilities are VERY limited)
  - Group the crashes for analysis

- Spider Pig
  - Created by Piotr Bania
  - Not available for testing, but from the paper: It is much more advanced them the provided tool (but well, it is not available?)
    - » Virtual Code Integration (or Dynamic Binary Rewriting) -> Discussed in my previous year presentation about Fuzzers here in Troopers
    - » Disputable Objects: Partially controlled data is analyzed using the parent data

- Taint Bochs
  - Used for tracking sensitive data lifecycle in memory

Existent Solutions and Comparisions

- Taint Check
  - Uses DynamicRIO or Valgrind
  - Taint Seed: Defining the tainted values (data comming from the network for example)
  - Taint Tracker: Tracks the propagation
  - Taint Assert: Alert about security violations
  - Used while testing software to detect overflow conditions, does nto really help in the exploit creation
    - » In the article I also provided a heap analysis tool for Embedded Linux Architecture (ARM) since the Memcheck plugin for Valgrind is not available on this architecture

- Bitblaze
  - An amazing platform for binary analysis
  - Provides better classification of exploitability (Charlie Miller talk in BH)
  - Can be used as base platform for the provided solution (VINE)

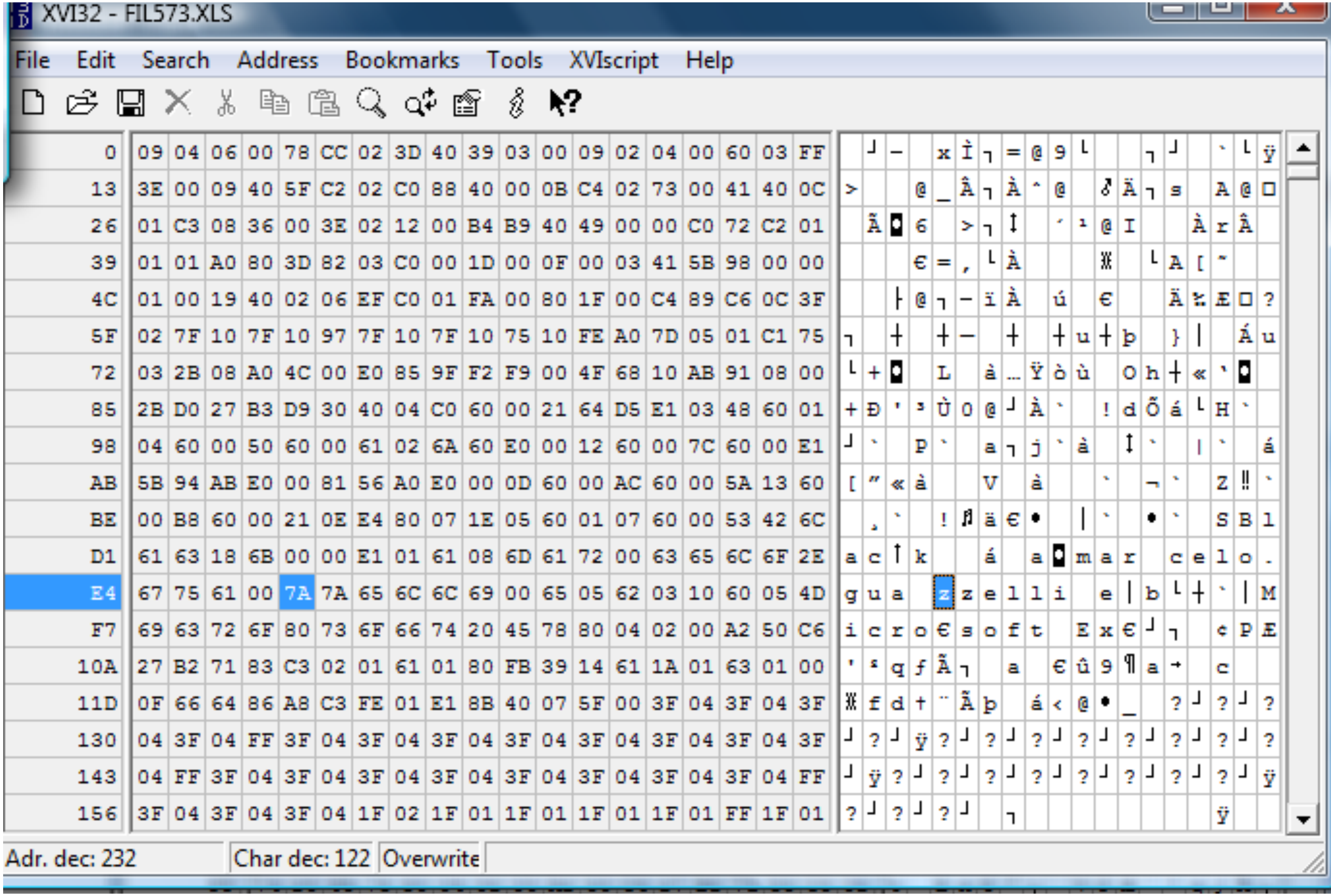
How it works (or is supposed to)

```
ModLoad: 75da0000 75e5d000   C:\WINDOWS\system32\SXS.DLL
(ac.594): Break instruction exception - code 80000003 (first chance)
eax=7ffdd000 ebx=00000001 ecx=00000002 edx=00000003 esi=00000004 edi=00000005
eip=7c81a3e1 esp=009bffcc ebp=009bfff4 iopl=0         nv up ei pl zr na pe nc
cs=001b  ss=0023  ds=0023  es=0023  fs=0038  gs=0000             efl=00000246
*** ERROR: Symbol file could not be found.  Defaulted to export symbols for C:\
ntdll!DbgBreakPoint:
7c81a3e1 cc              int     3
0:003> bp kernel32!CreateFileW
*** ERROR: Symbol file could not be found.  Defaulted to export symbols for C:\
0:003> g

*BUSY* Debuggee is running...
```

Start tracing

```
0:003> .load vdt-tracer
0:003> !vdt_help
Visual Data Tracer v1.0 Alpha - Copyright (C) 2008-2010
License: This software was created as companion to a Phrack Article.
Developed by Rodrigo Rubira Branco (BSDaemon) <rodrigo@risesecurity.org> and
Julio Auto <julio@julioauto.com>

!vdt_trace <filename>                                   - trace the program until a breakpoint or
                                                        in a file to be later consumed by the Vis
!vdt_help                                                                       - this help screen
0:003> !vdt_trace excel_phrack.vdt
```

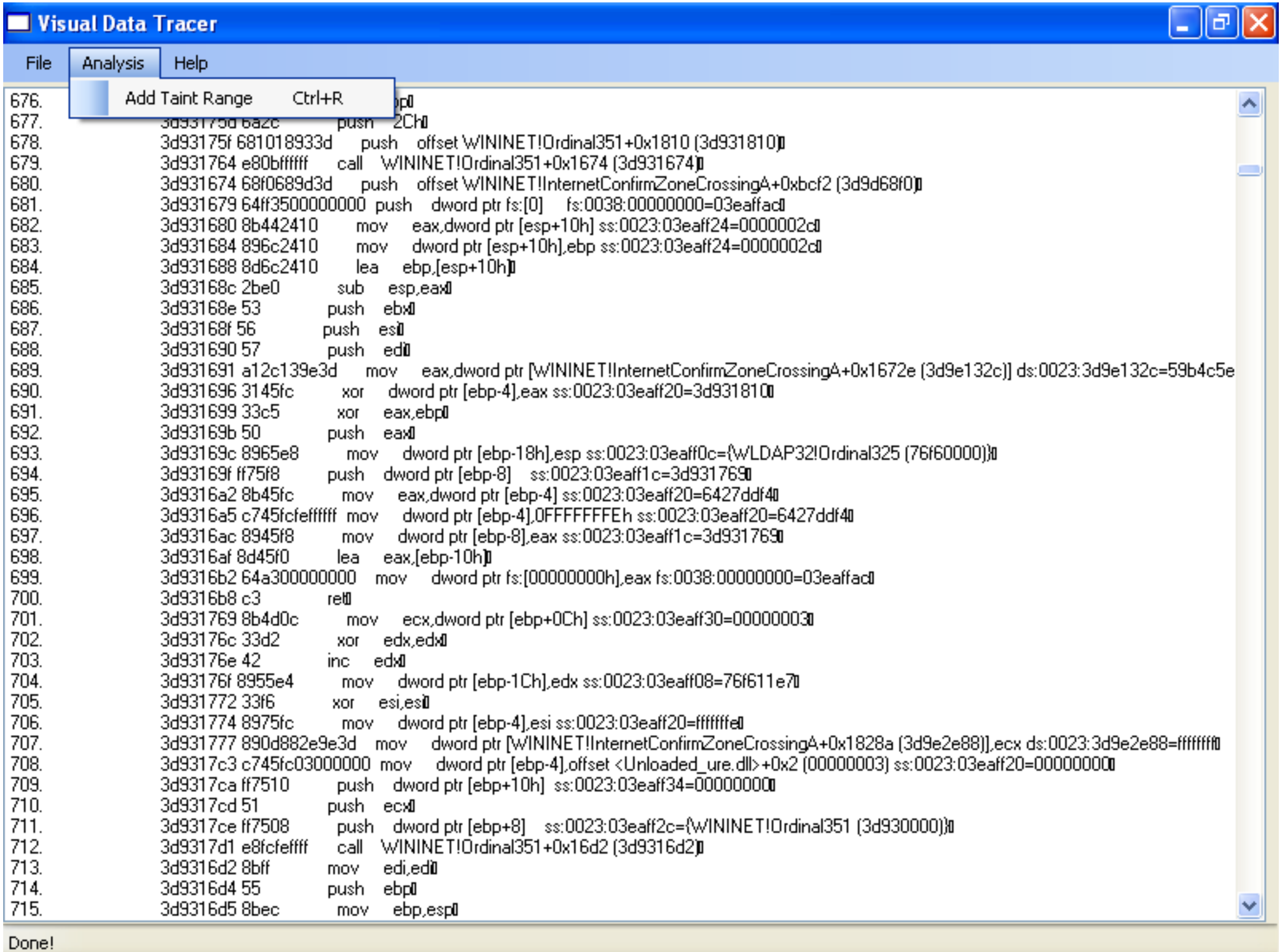
Find something from your input to search for in memory



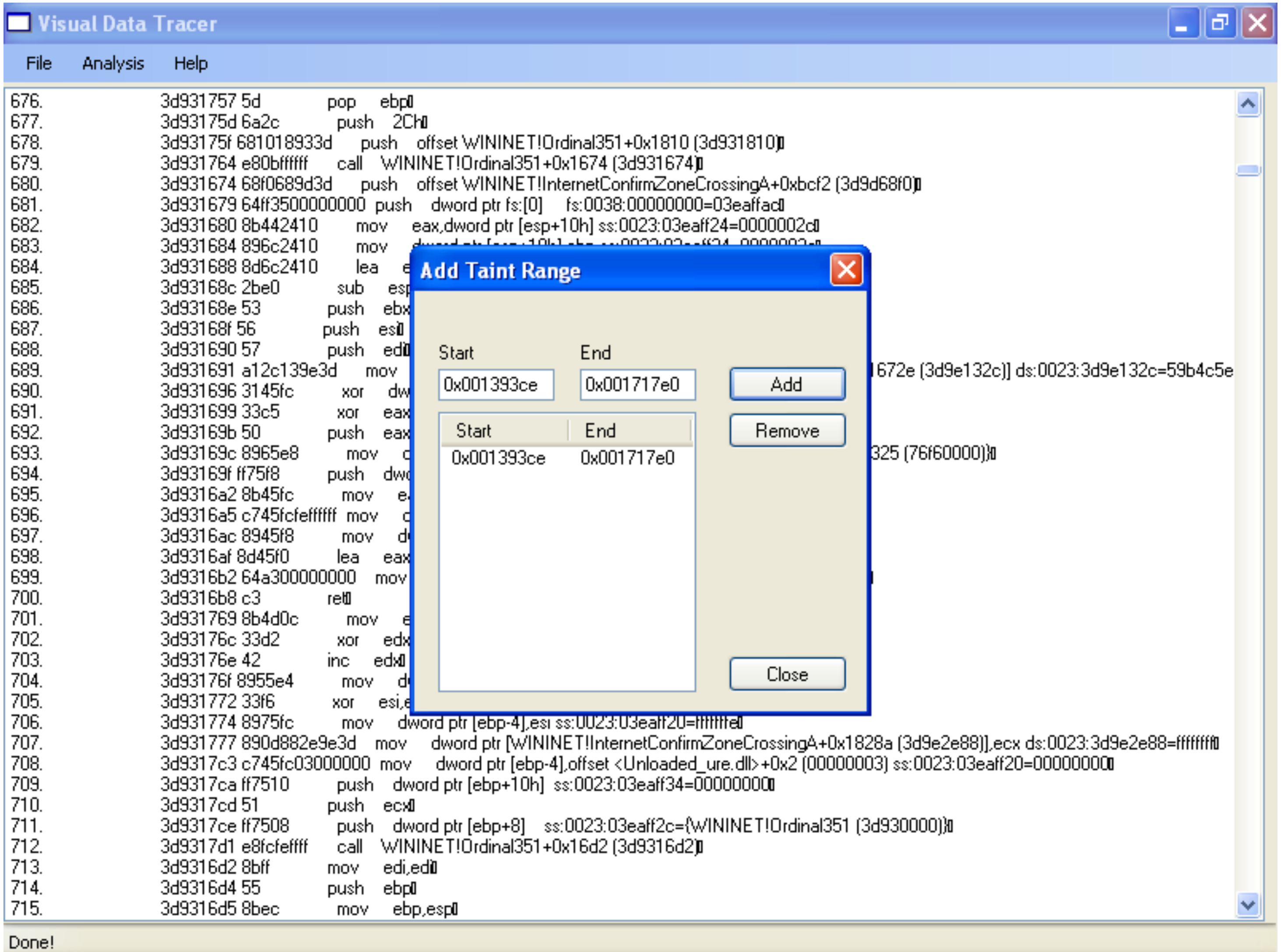
Locate the input in the program's memory

```
0:000> s -[w1]a 0x0 L?80000000 "zzelli"
0x001393ce
0x001717e0
0x30862168
```

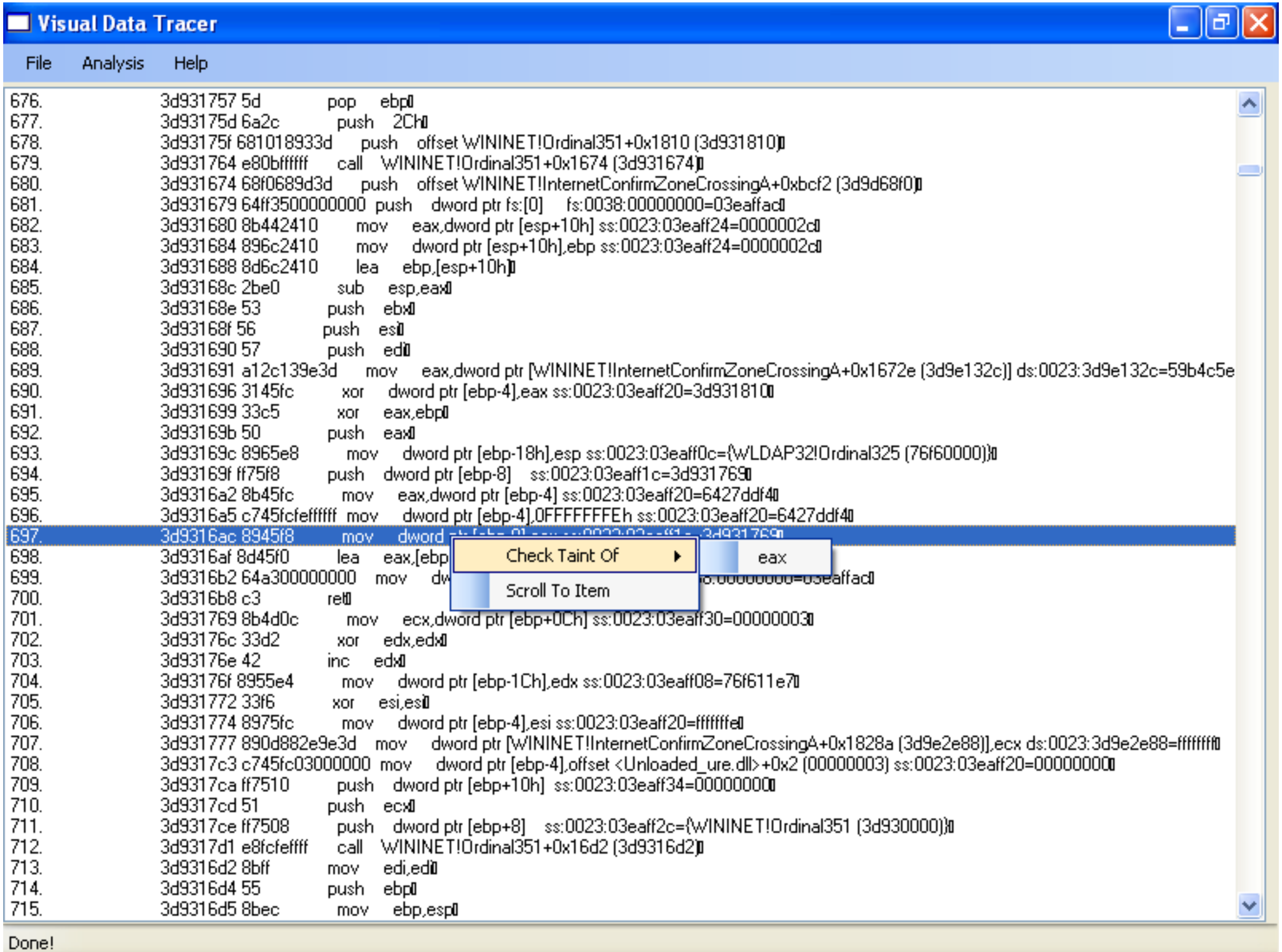
Open the tracing file



Add the taint range

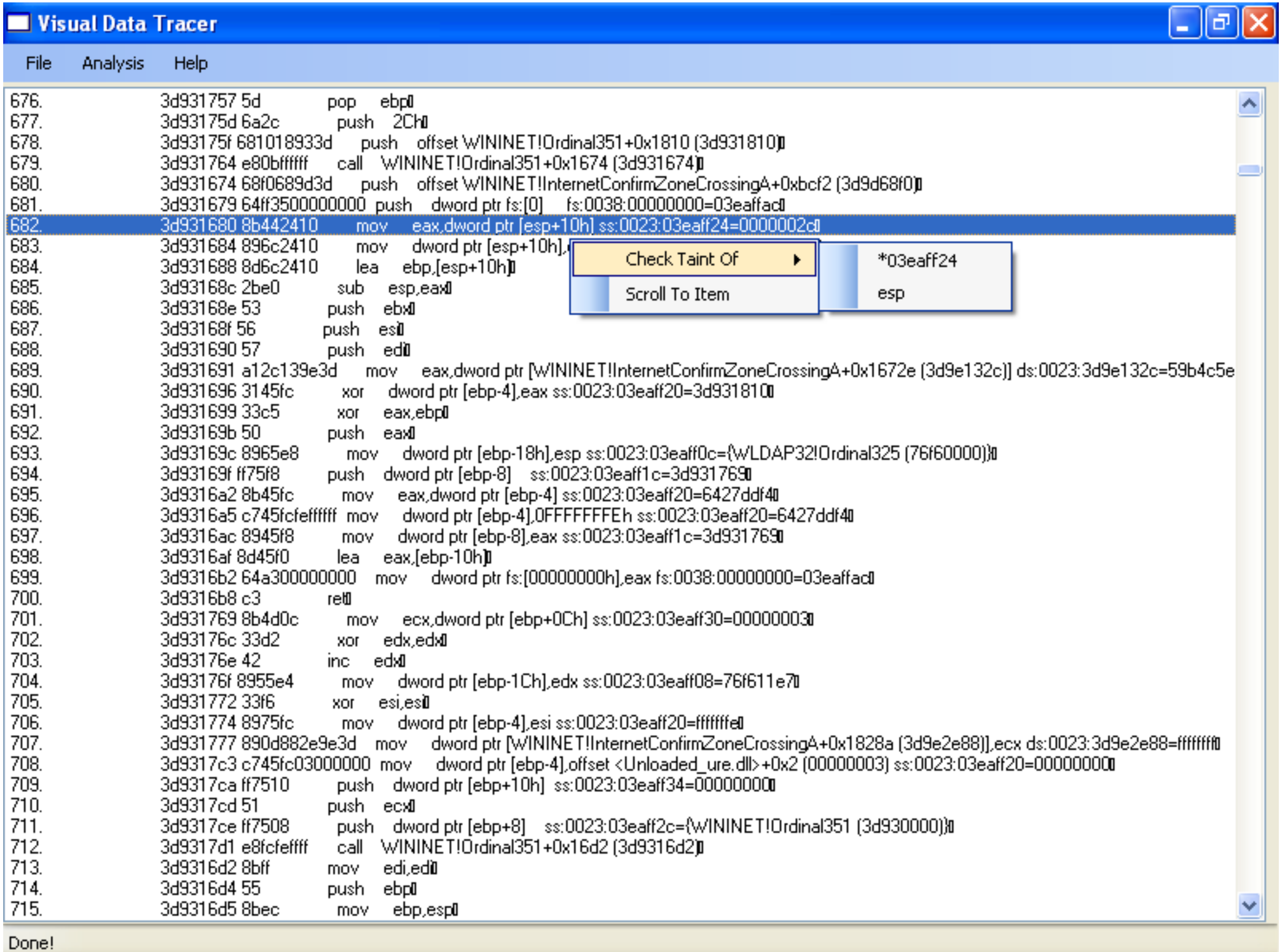


Analyze



Visual Data Tracer
File
Analysis
Help
676. 3d931757 5d pop ebp
677. 3d93175d 6a2c push 2Ch
678. 3d93175f 681018933d push offset WININET!Ordinal351+0x1810 (3d931810)
679. 3d931764 e80bffffff call WININET!Ordinal351+0x1674 (3d931674)
680. 3d931674 68f0689d3d push offset WININET!InternetConfirmZoneCrossingA+0xbcf2 (3d9d68f0)
681. 3d931679 64ff3500000000 push dword ptr fs:[0] fs:0038:00000000=03eaffac
682. 3d931680 8b442410 mov eax,dword ptr [esp+10h] ss:0023:03eaff24=0000002c
683. 3d931684 896c2410 mov dword ptr [esp+10h],ebp ss:0023:03eaff24=0000002c
684. 3d931688 8d6c2410 lea ebp,[esp+10h]
685. 3d93168c 2be0 sub esp,eax
686. 3d93168e 53 push ebx
687. 3d93168f 56 push esi
688. 3d931690 57 push edi
689. 3d931691 a12c139e3d mov eax,dword ptr [WININET!InternetConfirmZoneCrossingA+0x1672e (3d9e132c)] ds:0023:3d9e132c=59b4c5e
690. 3d931696 3145fc xor dword ptr [ebp-4],eax ss:0023:03eaff20=3d931810
691. 3d931699 33c5 xor eax,ebp
692. 3d93169b 50 push eax
693. 3d93169c 8965e8 mov dword ptr [ebp-18h],esp ss:0023:03eaff0c={WLDAP32!Ordinal325 (76f60000)}
694. 3d93169f ff75f8 push dword ptr [ebp-8] ss:0023:03eaff1c=3d931769
695. 3d9316a2 8b45fc mov eax,dword ptr [ebp-4] ss:0023:03eaff20=6427ddf4
696. 3d9316a5 c745fcfeffffff mov dword ptr [ebp-4],0FFFFFFFEh ss:0023:03eaff20=6427ddf4
697. 3d9316ac 8945f8 mov dword
698. 3d9316af 8d45f0 lea eax,[ebp
699. 3d9316b2 64a300000000 mov dw
700. 3d9316b8 c3 ret
Check Taint Of
Scroll To Item
eax
701. 3d931769 8b4d0c mov ecx,dword ptr [ebp+0Ch] ss:0023:03eaff30=00000003
702. 3d93176c 33d2 xor edx,edx
703. 3d93176e 42 inc edx
704. 3d93176f 8955e4 mov dword ptr [ebp-1Ch],edx ss:0023:03eaff08=76f611e7
705. 3d931772 33f6 xor esi,esi
706. 3d931774 8975fc mov dword ptr [ebp-4],esi ss:0023:03eaff20=fffffffe
707. 3d931777 890d882e9e3d mov dword ptr [WININET!InternetConfirmZoneCrossingA+0x1828a (3d9e2e88)],ecx ds:0023:3d9e2e88=ffffffff
708. 3d9317c3 c745fc03000000 mov dword ptr [ebp-4],offset <Unloaded_ure.dll>+0x2 (00000003) ss:0023:03eaff20=00000000
709. 3d9317ca ff7510 push dword ptr [ebp+10h] ss:0023:03eaff34=00000000
710. 3d9317cd 51 push ecx
711. 3d9317ce ff7508 push dword ptr [ebp+8] ss:0023:03eaff2c={WININET!Ordinal351 (3d930000)}
712. 3d9317d1 e8fcfeffff call WININET!Ordinal351+0x16d2 (3d9316d2)
713. 3d9316d2 8bff mov edi,edi
714. 3d9316d4 55 push ebp
715. 3d9316d5 8bec mov ebp,esp
Done!

Analyze


Visual Data Tracer
File Analysis Help
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683. 3d931684 896c2410 mov dword ptr [esp+10h],
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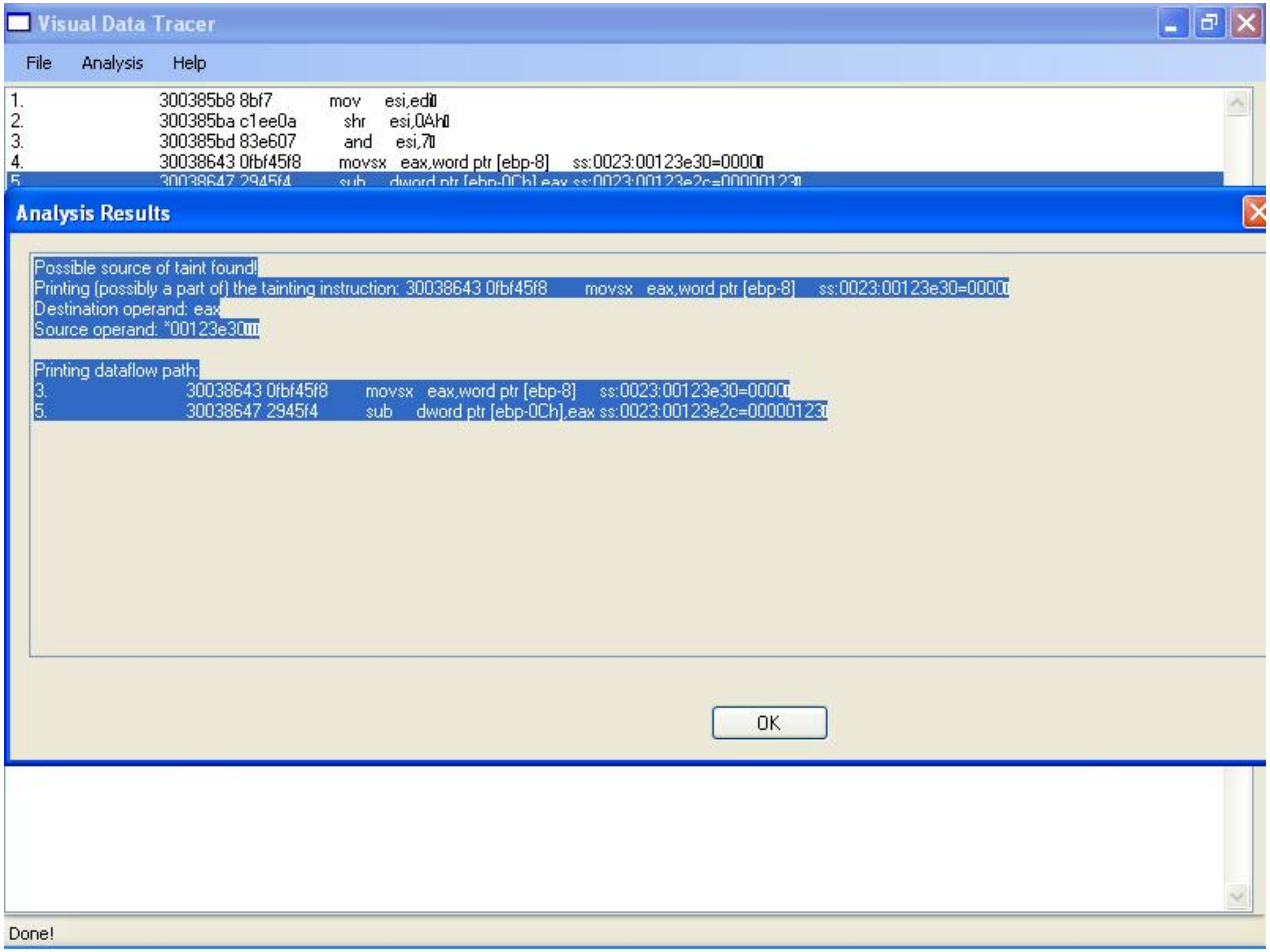
689. 3d931691 a12c139e3d mov eax,dword ptr [WININET!InternetConfirmZoneCrossingA+0x1672e (3d9e132c)] ds:0023:3d9e132c=59b4c5e
690. 3d931696 3145fc xor dword ptr [ebp-4],eax ss:0023:03eaff20=3d931810
691. 3d931699 33c5 xor eax,ebp
692. 3d93169b 50 push eax
693. 3d93169c 8965e8 mov dword ptr [ebp-18h],esp ss:0023:03eaff0c={WLDAP32!Ordinal325 (76f60000)}
694. 3d93169f ff75f8 push dword ptr [ebp-8] ss:0023:03eaff1c=3d931769
695. 3d9316a2 8b45fc mov eax,dword ptr [ebp-4] ss:0023:03eaff20=6427ddf4
696. 3d9316a5 c745fcfeffffff mov dword ptr [ebp-4],0FFFFFFFEh ss:0023:03eaff20=6427ddf4
697. 3d9316ac 8945f8 mov dword ptr [ebp-8],eax ss:0023:03eaff1c=3d931769
698. 3d9316af 8d45f0 lea eax,[ebp-10h]
699. 3d9316b2 64a300000000 mov dword ptr fs:[00000000h],eax fs:0038:00000000=03eaffac
700. 3d9316b8 c3 ret
701. 3d931769 8b4d0c mov ecx,dword ptr [ebp+0Ch] ss:0023:03eaff30=00000003
702. 3d93176c 33d2 xor edx,edx
703. 3d93176e 42 inc edx
704. 3d93176f 8955e4 mov dword ptr [ebp-1Ch],edx ss:0023:03eaff08=76f611e7
705. 3d931772 33f6 xor esi,esi
706. 3d931774 8975fc mov dword ptr [ebp-4],esi ss:0023:03eaff20=fffffffe
707. 3d931777 890d882e9e3d mov dword ptr [WININET!InternetConfirmZoneCrossingA+0x1828a (3d9e2e88)],ecx ds:0023:3d9e2e88=ffffffff
708. 3d9317c3 c745fc03000000 mov dword ptr [ebp-4],offset <Unloaded_ure.dll>+0x2 (00000003) ss:0023:03eaff20=00000000
709. 3d9317ca ff7510 push dword ptr [ebp+10h] ss:0023:03eaff34=00000000
710. 3d9317cd 51 push ecx
711. 3d9317ce ff7508 push dword ptr [ebp+8] ss:0023:03eaff2c={WININET!Ordinal351 (3d930000)}
712. 3d9317d1 e8fcfeffff call WININET!Ordinal351+0x16d2 (3d9316d2)
713. 3d9316d2 8bff mov edi,edi
714. 3d9316d4 55 push ebp
715. 3d9316d5 8bec mov ebp,esp
Check Taint Of
Scroll To Item
*03eaff24
esp
Done!

Analyze


Visual Data Tracer
File
Analysis
Help
1. 300385b8 8bf7 mov esi,edi
2. 300385ba c1ee0a shr esi,0Ah
3. 300385bd 83e607 and esi,7
4. 30038643 0fbf45f8 movsx eax,word ptr [ebp-8] ss:0023:00123e30=0000
Analysis Results
Possible source of taint found!
Printing (possibly a part of) the tainting instruction: 30038643 0fbf45f8 movsx eax,word ptr [ebp-8] ss:0023:00123e30=0000
Destination operand: eax
Source operand: *00123e30
Printing dataflow path:
3. 30038643 0fbf45f8 movsx eax,word ptr [ebp-8] ss:0023:00123e30=0000
5. 30038647 2945f4 sub dword ptr [ebp-0Ch],eax ss:0023:00123e2c=00000123
OK
Done!

Future

- I can’t foresee the future!
- Hope more researchers will contribute in the future
- The code needs immediate support for extended coverage of x86 instructions, speed enhancements, introduction of heuristical detection over user input (so you don’t need to specify memory ranges to watch)

Special Thanks

- To the Troopers Staff, for trusting me once again... This conference is awesome
- Prime Security Team, specially Filipe Balestra
- RISE Security Group, yeah, we still exist, but now everybody works
- Special thanks to Julio Auto who developed everything with me (and besides me, lots of patience I know...)

End! Really !?

Rodrigo Rubira Branco (BSDaemon)

Founder Dissect || PE – Now the Qualys Vulnerability & Malware Research Lab

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