

For Realz Mode!

Reversing an MBR from the CSAW CTF
(and how to write a keygen with a SAT solver)

t0x0 @numinit

V A P O R S E C

2017-10-11

About us

■ @numinit

- Software developer by day
- Tinkerer on everything by night
- First Def Con and Toorcon experiences this year
- Doing CSAW CTF for a while

■ t0x0 (@t0x0pg)

- Writes lots of interpreted code
- Lives mostly in Windows world
- Jack of all trades, master of none (so far)
- Obsessively curious

What's CSAW?

An annual security capture the flag run by New York Polytechnic that contains challenges with a **wide range of difficulties**, attracting everyone from undergraduates to well-known teams like PPP

CSAW'17



CAPTURE
THE FLAG

<p>Crypto</p> <p>baby_crypt</p> <p>350</p>	<p>Reversing</p> <p>Gopherz</p> <p>350</p>	<p>Pwn</p> <p>FIREWALL</p> <p>400</p>
<p>Reversing</p> <p>bananaScript</p> <p>450</p>	<p>Pwn</p> <p>Minesweeper</p> <p>500</p>	<p>Reversing</p> <p>GrumpCheck</p> <p>500</p>

Who are V A P O R S E C ?

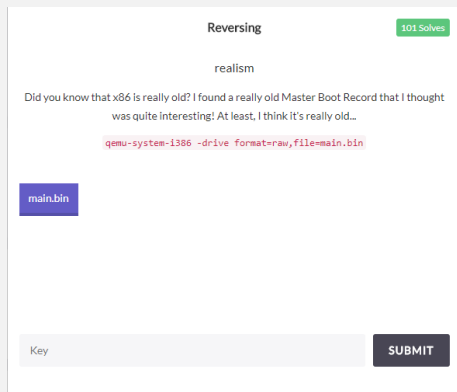
- A new A E S T H E T I C San Diego CTF team
- Had 10 participants during the CSAW CTF
- Got 15th in CSAW industry professional bracket, which is cool I guess

Outline

- 1 Introduction
- 2 Reversing the MBR
- 3 Finding the flag

RE400 what?...

- Challenge worth 400 points
- Reverse Engineering category
- We get some hints right away...
 - This is an MBR
 - ...from an x86 system



A place to start...

- Wikipedia, of course!



The screenshot shows the Wikipedia article for "Master boot record". At the top left is the Wikipedia logo, a globe with various symbols, and the text "WIKIPEDIA The Free Encyclopedia". Below this is a sidebar with links: "Main page", "Contents", "Featured content", "Current events", "Random article", "Donate to Wikipedia", "Wikipedia store", "Interaction", "Help", "About Wikipedia", "Community portal", "Recent changes", "Contact page", "Tools", "What links here", and "Related changes". The main content area has a tabbed interface with "Article" and "Talk" tabs. The title "Master boot record" is prominently displayed. Below the title, it says "From Wikipedia, the free encyclopedia". The article text begins with "This article is about a PC-specific type of boot sector c..." and "A **master boot record (MBR)** is a special type of boot sector intended for use with **IBM PC-compatible** systems and be...". It continues with "The MBR holds the information on how the logical partition function as a loader for the installed operating system—us... record (VBR). This MBR code is usually referred to as a b...". Another paragraph starts with "The organization of the partition table in the MBR limits the limit assuming 33-bit arithmetics or 4096-byte sectors are operating systems and system tools, and can cause serious partitioning scheme is in the process of being superseded provide some limited form of backward compatibility for old MBRs are not present on non-partitioned media such as fl...". At the bottom of the article, there is a "Contents" section with a "[hide]" link and a list item "1 Overview".

A place to start...

- Wikipedia, of course!
 - 512 bytes
 - MBR signature: 55 AA
 - "expected to contain real mode machine language instructions"
 - little-endian
 - loads at 0000:7C00



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Article Talk

Master boot record

From Wikipedia, the free encyclopedia

This article is about a PC-specific type of boot sector c...

A **master boot record (MBR)** is a special type of boot sector intended for use with **IBM PC-compatible** systems and begins with the signature 0x55AA.

The MBR holds the information on how the logical partitioning function as a loader for the installed operating system—usually using a boot sector (VBR). This MBR code is usually referred to as a boot code.

The organization of the partition table in the MBR limits the number of partitions by assuming 33-bit arithmetics or 4096-byte sectors are used. The partitioning scheme is in the process of being superseded by GUID Partition Table (GPT) and MBRs provide some limited form of backward compatibility for older operating systems.

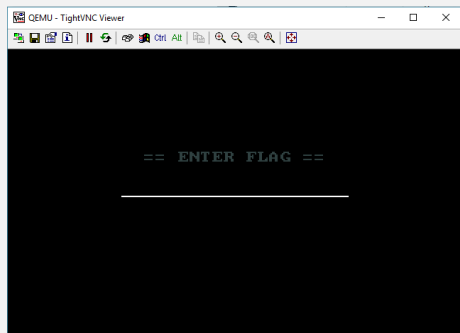
MBRs are not present on non-partitioned media such as flash drives.

Contents [hide]

- 1 Overview

Tool Time!...

- qemu (gift wrapped)
 - -s (gdb)
 - -S (suspend)
 - -vnc:1



Tool Time!...

- qemu (gift wrapped)
 - QEMU/Monitor
 - info registers
 - system reset

```
ES =9f40 0009f400 0000ffff 00009300
CS =f000 000f0000 0000ffff 00009b00
SS =0000 00000000 0000ffff 00009300
DS =0000 00000000 0000ffff 00009300
FS =0000 00000000 0000ffff 00009300
GS =0000 00000000 0000ffff 00009300
LDT=0000 00000000 0000ffff 00008200
TR =0000 00000000 0000ffff 00008b00
GDT= 000fd3a8 00000037
IDT= 00000000 000003ff
CR0=00000012 CR2=00000000 CR3=00000000 CR4=00000600
DR0=00000000 DR1=00000000 DR2=00000000 DR3=00000000
DR6=ffff0ff0 DR7=00000400
EFER=0000000000000000
FCW=037f FSM=0000 [ST=0] FTW=00 MXCSR=00001f80
FPR0=0000000000000000 0000 FPR1=0000000000000000 0000
FPR2=0000000000000000 0000 FPR3=0000000000000000 0000
FPR4=0000000000000000 0000 FPR5=0000000000000000 0000
FPR6=0000000000000000 0000 FPR7=0000000000000000 0000
XMM00=00000000000000000000000000000000 XMM01=00000000000000000000000000000000
XMM02=00000000000000000000000000000000 XMM03=00000000000000000000000000000000
XMM04=00000000000000000000000000000000 XMM05=00000000000000000000000000000000
XMM06=00000000000000000000000000000000 XMM07=00000000000000000000000000000000
(qemu) █
```

A quick recap...

- We have an x86 boot sector that's asking us for the flag



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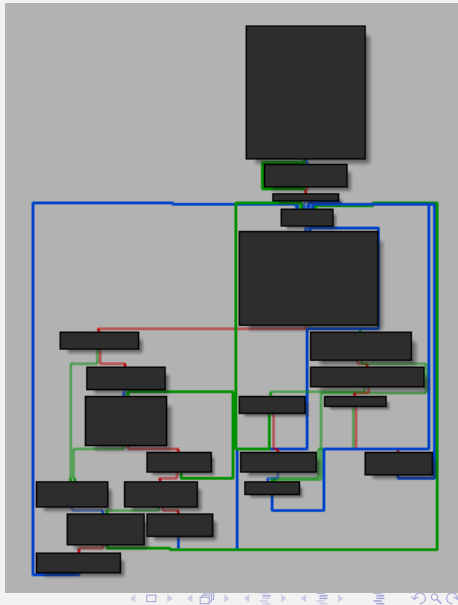
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 - ...but not in plaintext, because this is a 400 point challenge and that would be too easy
- So, where is it?



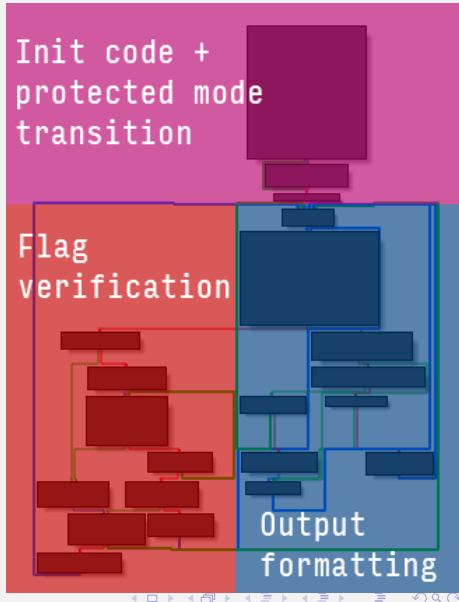
Reversing the boot sector

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Reversing the boot sector

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- We can visally pick out three sections:
 - Init code (responsible for the protected mode transition)
 - Display code (identifiable by a large number of `int` instructions)
 - Some other code that uses Intel SSE2 instructions



First leads

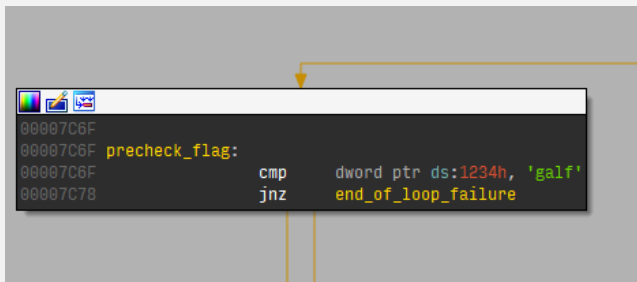
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- The flag is **hashed** using a **custom algorithm** implemented with Intel SSE instructions
- *Ugh...*
- We have to find an input to the hash algorithm that hashes to the same value that's stored in the boot sector

Suddenly, SSE2 instructions

“My Intel CPU can do *that?*”

The author of the challenge decided to use a bunch of obscure x86 SSE2 instructions to force us to trawl through Intel documentation

Note

SSE2 instructions operate on XMM registers, which are 128 bits (16 bytes) wide.

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Question

Why are these instructions useful for writing a hash function (even if it's a bad hash function that we can break?)

Packed Sum of Absolute Differences of Bytes in Word

That's a mouthful...

xmm0:

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
---	---	---	---	---	---	---	---	---	---	----	----	----	----	----	----

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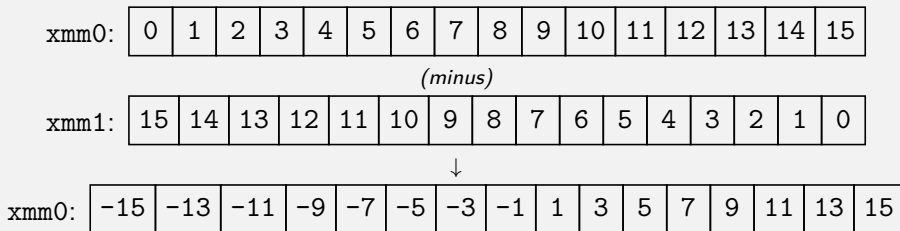


It's hard to go back...

If you just have the result, you have to find two sets of eight bytes where the absolute values of their differences sum to 64 (and there are many)

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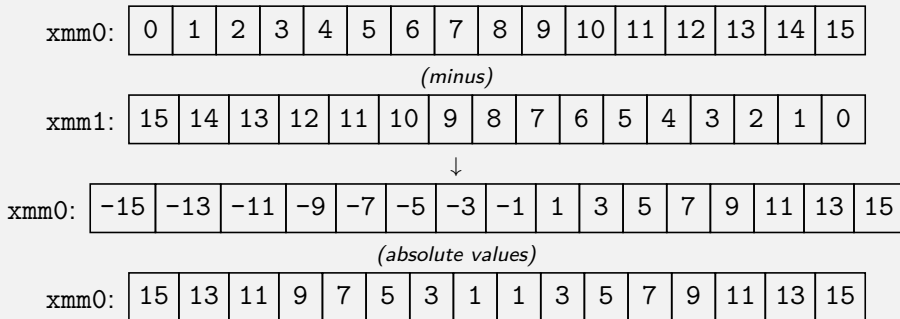


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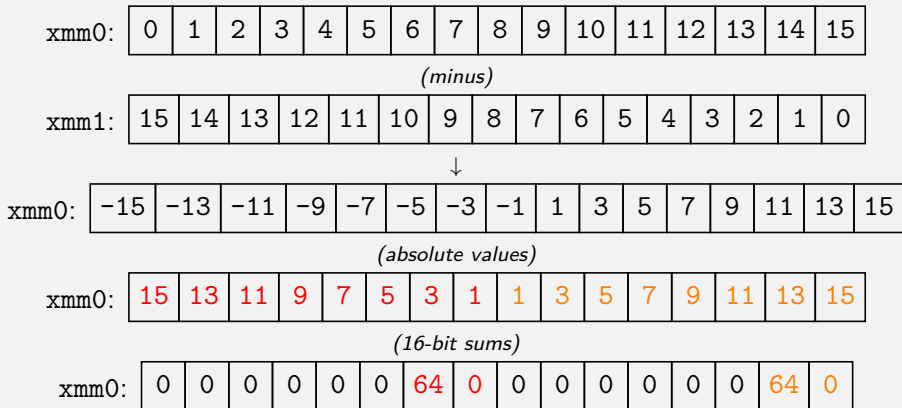


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SAT solvers to the rescue!

How to master Sudoku without memorizing strategies

"I think a serious case can be made that the decline in the American economy can be blamed on the sapping of the mental energy and productivity of the American workforce that sudoku addiction alone has wrought"

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Notice anything strange about this puzzle?

d	c	6	1	9	0	e	b	5	7	3	2	4	8	f	a
5	8	a	4	f	c	2	d	9	0	b	e	3	7	6	1
2	b	9	7	5	3	6	1	4	8	a	f	d	0	e	c
0	3	f	e	4	a	8	7	d	c	6	1	9	b	2	5
8	d	c	6	1	9	3	2	b	5	e	7	0	4	a	f
b	1	5	0	d	8	c	6	f	a	9	4	7	2	3	e
9	a	4	f	7	5	0	e	2	3	1	8	b	d	c	6
7	2	e	3	b	4	a	f	0	d	c	6	1	9	5	8
e	4	d	c	6	1	9	0	a	b	2	5	8	f	7	3
1	9	8	2	3	7	5	4	e	6	f	0	a	c	d	b
f	6	7	a	2	d	b	c	1	9	8	3	5	e	0	4
3	5	0	b	a	e	f	8	7	4	d	c	6	1	9	2
a	e	3	d	c	6	1	9	8	f	7	b	2	5	4	0
6	0	2	5	e	b	d	3	c	1	4	9	f	a	8	7
c	7	1	9	8	f	4	5	6	2	0	a	e	3	b	d
4	f	b	8	0	2	7	a	3	e	5	d	c	6	1	9

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Stranger still: a SAT solver created it from thin air

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2	b	9	7	5	3	6	1	4	8	a	f	d	0	e	c
0	3	f	e	4	a	8	7	d	c	6	1	9	b	2	5
8	d	c	6	1	9	3	2	b	5	e	7	0	4	a	f
b	1	5	0	d	8	c	6	f	a	9	4	7	2	3	e
9	a	4	f	7	5	0	e	2	3	1	8	b	d	c	6
7	2	e	3	b	4	a	f	0	d	c	6	1	9	5	8
e	4	d	c	6	1	9	0	a	b	2	5	8	f	7	3
1	9	8	2	3	7	5	4	e	6	f	0	a	c	d	b
f	6	7	a	2	d	b	c	1	9	8	3	5	e	0	4
3	5	0	b	a	e	f	8	7	4	d	c	6	1	9	2
a	e	3	d	c	6	1	9	8	f	7	b	2	5	4	0
6	0	2	5	e	b	d	3	c	1	4	9	f	a	8	7
c	7	1	9	8	f	4	5	6	2	0	a	e	3	b	d
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■ Symbolic execution engines

- Convert CPU instructions into a SMT solver language

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SMT solvers let you write a type of SQL that can be used
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The SMT query itself can be constructed from a language like Python, C, or even raw x86 assembly

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We'll be mainly focusing on using Z3, since all the other tools use it under the hood (and it's awesome)

Back to our sudoku...

How do you create a hexadoku puzzle out of thin air with Z3?

Back to our sudoku...

How do you create a hexadoku puzzle out of thin air with Z3?

Creating the board

```
import z3

# Define a 16x16 Sudoku
order = 4
side = order ** 2

# Create a solver
smt = z3.Solver()

cells = [list() for row in range(side)]
for r in range(side):
    for c in range(side):
        cells[r].append(z3.Int('cell_%d_%d' % (r, c)))
```

Telling z3 how to play sudoku

We'll define our first rule: each cell has to be between 0 and 15

Telling z3 how to play sudoku

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The most basic of Sudoku rules

```
for r in range(side):  
    for c in range(side):  
        # Each cell must be between 0 and 15  
        smt.add(z3.And(cells[r][c] >= 0, cells[r][c] < side))
```

Telling z3 how to play sudoku

Now, the rules everyone knows

Telling z3 how to play sudoku

Now, the rules everyone knows

Rows and columns

```
# Rows must have unique values
for r in range(side):
    this_row = [cells[r][c] for c in range(side)]
    smt.add(z3.Distinct(*this_row))

# Columns must have unique values
for c in range(side):
    this_col = [cells[r][c] for r in range(side)]
    smt.add(z3.Distinct(*this_col))
```

Telling z3 how to play sudoku

Mini-boxes are slightly more complicated

Telling z3 how to play sudoku

Mini-boxes are slightly more complicated

Mini-boxes

```
# Each mini-box must have unique values
for r in range(0, side, order):
    for c in range(0, side, order):
        selected = []
        for i in range(box_size):
            for j in range(box_size):
                selected.append(cells[r + i][c + j])

        smt.add(z3.Distinct(*selected))
```

Telling z3 how to play *our version of* sudoku

Now for the initial values

... dc858 isn't as sudoku-able :-)

Telling z3 how to play *our version of* sudoku

Now for the initial values

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Initial values

```
# Now, define the initial values
```

```
smt.add(cells[0][0] == 0xd)
```

```
smt.add(cells[0][1] == 0xc)
```

```
smt.add(cells[0][2] == 0x6)
```

```
smt.add(cells[0][3] == 0x1)
```

```
smt.add(cells[0][4] == 0x9)
```

```
# ... etc.
```

Telling z3 to start solving, and printing the result

This will take a little bit of time

Telling z3 to start solving, and printing the result

This will take a little bit of time

Start solving!

```
if smt.check() == z3.unsat:
    print('Sudoku is impossible to solve :(')
else:
    model = smt.model()

    # Retrieve each cell from the model as a python long
    result = [list() for row in range(side)]
    for r in range(side):
        for c in range(side):
            cell = model[r][c]
            print('%x ' % model[cell].as_long(), end='')
    print()
```

The results...

d	c	6	1	9	0	e	b	5	7	3	2	4	8	f	a
5	8	a	4	f	c	2	d	9	0	b	e	3	7	6	1
2	b	9	7	5	3	6	1	4	8	a	f	d	0	e	c
0	3	f	e	4	a	8	7	d	c	6	1	9	b	2	5
8	d	c	6	1	9	3	2	b	5	e	7	0	4	a	f
b	1	5	0	d	8	c	6	f	a	9	4	7	2	3	e
9	a	4	f	7	5	0	e	2	3	1	8	b	d	c	6
7	2	e	3	b	4	a	f	0	d	c	6	1	9	5	8
e	4	d	c	6	1	9	0	a	b	2	5	8	f	7	3
1	9	8	2	3	7	5	4	e	6	f	0	a	c	d	b
f	6	7	a	2	d	b	c	1	9	8	3	5	e	0	4
3	5	0	b	a	e	f	8	7	4	d	c	6	1	9	2
a	e	3	d	c	6	1	9	8	f	7	b	2	5	4	0
6	0	2	5	e	b	d	3	c	1	4	9	f	a	8	7
c	7	1	9	8	f	4	5	6	2	0	a	e	3	b	d
4	f	b	8	0	2	7	a	3	e	5	d	c	6	1	9

The power of SMT solvers

Maybe familiar to anyone who's tried Prolog

We only had to **define the constraints of the puzzle we wanted**, and Z3 found one satisfying those constraints

Constraint solving our boot sector

“Hey, Z3, I want you to find me input values that, after being put through this crazy operation, end up being equal to the ones stored in the boot sector”

xmm0:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
-------	---	---	---	---	---	---	---	---	---	---	----	----	----	----	----	----

(minus)

xmm1:	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
-------	----	----	----	----	----	----	---	---	---	---	---	---	---	---	---	---



xmm0:	-15	-13	-11	-9	-7	-5	-3	-1	1	3	5	7	9	11	13	15
-------	-----	-----	-----	----	----	----	----	----	---	---	---	---	---	----	----	----

(absolute values)

xmm0:	15	13	11	9	7	5	3	1	1	3	5	7	9	11	13	15
-------	----	----	----	---	---	---	---	---	---	---	---	---	---	----	----	----

(16-bit sums)

xmm0:	0	0	0	0	0	0	64	0	0	0	0	0	0	0	64	0
-------	---	---	---	---	---	---	----	---	---	---	---	---	---	---	----	---