

Malbolge: Welcome to Hell

Anna J. Carvalho

School of Computing, Grand Valley State University

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Professor Ira Woodring

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0. History

Malbolge, named after the eighth circle of hell in Dante's *Inferno*, is an esoteric programming language created by Ben Olmstead in 1998. Malbolge was created with the goal of being the most difficult language to program in; in fact, Malbolge is so difficult to understand that its own creator has never written a single program in it.

The first Malbolge program wasn't written until a whole two years after its creation and it wasn't even written by a human being—rather, it was produced by a Lisp program using a beam search algorithm. What was this program that took two years to write, you ask? A program that prints “Hello, world!”.

```
(=<`#9]~6ZY327Uv4-QsqpMn&+Ij" 'E%e{Ab~w=_:]Kw%o44Uqp0/Q?xNvL:`H%c#DD2^WV>gY;  
dts76qKJImZkj
```

A Malbolge program that prints “Hello, world!”

The ‘Hello, world!’ program remained the most complex Malbolge program for several years, until in 2004, a man by the name of Lou Scheffer wrote a non-terminating Malbolge program that would copy its input to output. This was a groundbreaking achievement for the language, but it was trivial compared to the ‘99 bottles of beer’ program that was written a year later by some Japanese researchers at IEICE (Institute of Electronics, Information and Communication Engineers) that utilized a combination of loops, conditional branches, and arithmetic operations; something previously thought to be impossible for the language [2].

1. The Basics

Malbolge is an untyped, imperative language that takes concepts from earlier esoteric languages such as Brainf**k, INTERCAL, and Befunge and adds a whole other level of chaos. Aside from its complete lack of readability or writability, what makes this language so difficult to program in is the inclusion of a counter-intuitive *crazy operation*, ternary logic, and self-modifying code [6].

1.1. Memory

The Malbolge virtual machine works in *ternary* (trinary/base 3) and has a memory space of exactly 59049 machine words. A machine word is 10 *trits* (**tr**inary **di**gits) wide, allowing for a maximum possible value of 59048; memory addresses are also 10 trits wide.

Code and data are stored together in the same memory space and programs are fed directly into the virtual machine's memory segment starting at position 0. All whitespace is ignored, and if the interpreter encounters anything that is not whitespace and is not one of Malbolge's eight instructions, it will throw an error. Each word in the remaining memory is initialized as the result of performing the crazy operation (see section 1.3) on the contents of the two previous memory cells [6].

1.2. Registers

Malbolge has three registers: The *code pointer* **C**, the *data pointer* **D**, and the *accumulator* **A**. **C** points to the current instruction to be executed, **D** points to a word in memory and is used for data manipulation, and **A** holds the value of a word and is also used for data manipulation. All registers are initialized to 0 and both registers **C** and **D** are incremented after each instruction. Note: **[C]** represents the value pointed to by **C**, likewise with **D**.

1.3. Instructions

Malbolge only has eight instructions represented by the ASCII values **j**, **i**, *****, **<**, **p**, **v**, **/**, and **o**. Please see the table in appendix A for a summary of each instruction.

The “crazy” operation is a trit-wise function and is defined according to the following table:

| | | A | | |
|-----|---|---|---|---|
| | | 0 | 1 | 2 |
| [D] | 0 | 1 | 0 | 0 |
| | 1 | 1 | 0 | 2 |
| | 2 | 2 | 2 | 1 |

A couple things to notice about the crazy operator:

1. If **[D]** is all 1s, then the result is the value of **A** with the 0s and 1s swapped.
2. If **A** is all 2s, then the result is the value of **[D]** with the 1s and 2s swapped.

As *crazy* as the crazy operator looks, it does have its uses. At a minimum, it allows us to synthesize loads and stores. We will discuss this more in-depth in section 2.3.

1.4. Executing and Encrypting Instructions

In order to determine the instruction to be executed, the interpreter first verifies that the current (non-whitespace) instruction is a printable ASCII character (within the range 33-126). If it is, then it executes the instruction generated by the result of $([C] + C) \% 94$. Otherwise, the program is terminated.

If the instruction to be executed is none of the eight instructions shown in the table above, it is treated as a `Nop`. However, the only `Nop` instructions allowed in the source code are those for which $([C] + C) \% 94 = 68$. Thus, only `'`, `(`, `>`, `D`, `Q`, `b`, `c`, and `u` are allowed in the first memory position in the source code, `&`, `'`, `=`, `C`, `P`, `a`, `b`, and `t` in the second, etc. [6].

After an instruction is executed, it is encrypted according to the following definition:

ORIGINAL :

```
!"#$%&'()*+,-./0123456789:;<=>?@ABCDEFGHIJKLMNOPQRSTUVWXYZ[\]^_`abcdefghijklmnopqrstuvwxyz{|}~
```

AFTER ENCRYPTION:

```
5z]&gqtyfr$(we4{WP)H-Zn,[%\3dL+Q;>U!pJS72Fh0A1CB6v^=I_0/8|jsb9m<.TVac`uY*MK'X~xD  
l}REokN:#?G"i@
```

For example: `!` becomes `5`, `"` becomes `z`, etc. [6].

2. Techniques for Programming in Malbolge

The idea of programming in this godforsaken language might seem daunting. However, Malbolge does have quite a few “weaknesses” that can be taken advantage of to make writing Malbolge programs just barely less difficult.

2.1. Using the Jump Instruction for Flow Control

Unlike every other instruction in Malbolge, the `Jmp` instruction does not get encrypted after execution. To explain why, let’s first review the order in which Malbolge executes instructions:

1. Execute the instruction in `[C]`
2. Encrypt `[C]`
3. Increment `C` and `D`

Because the `Jmp` instruction is the only instruction that changes the value of `[C]` during execution (between steps 1 and 2), what actually gets encrypted is the address of the intended jump target [3]. This gives us a huge advantage when writing Malbolge programs because it allows us to control the flow of the program.

2.2. Taking Advantage of Cycles

After an instruction is encrypted, it is not completely useless afterwards like you might think. Encrypting an instruction will turn it into a different instruction, and then maybe a few more, until it’s eventually

encrypted back into the original instruction, thus creating a cycle. These cycles can be of lengths 2, 4, 5, 6, 9, and 68, but generally, the shorter the cycle, the more useful it is to the programmer [2].

The length and order of a cycle depends entirely on the address (modulo 94) at which the instruction is located. For example, a cycle that looks like `In/Nop` can only exist at addresses 43 and 47, while a cycle that looks like `Nop/In/Nop/Nop/MovD/Nop` can only exist at address 14 [4].

We can use these cycles in combination with the jump instruction to create *routines*. These routines come in handy when we want to have loops in our program, requiring us to execute the same instructions multiple times. One example of how we might use these in our program is by creating a routine for each Malbolge instruction so that we are able to use them reliably over and over again. For example, suppose we wanted to do the following:

`In` → `Out` → `MovD`.

We *could* do this at any location, but we would only be able to execute it once (and have it do the intended thing). Instead, we can be smart about where we put our instructions in memory and then jump to each one as needed.

We start by creating routines for the `In`, `Out`, and `MovD` instructions using xlat2 cycles (cycles of length 2 containing at least one `Nop`), each followed by a `Jmp` instruction. There exists an `In/Nop` cycle at address 43, an `Out/Nop` cycle at address 25, and a `MovD/Nop` cycle at address 60 [4]. Putting it all together, we get:

`Jmp to 43` → `In/Nop` → `Jmp to 25` → `Out/Nop` → `Jmp to 60` → `MovD/Nop` → `Jmp`

Where the bolded instructions indicate where we are in the cycle. Then the next time we want to execute it, it will look like:

`Jmp to 43` → **`In/Nop`** → `Jmp to 25` → **`Out/Nop`** → `Jmp to 60` → **`MovD/Nop`** → `Jmp`

And so on.

2.3. Pseudo Loads and Stores

Malbolge has no built-in load or store instructions. However, we can synthesize a load and store with the `Rot` and `Opr` instructions because they are the only two Malbolge instructions that modify the data in memory.

Synthesizing a load is relatively straightforward. Let's assume `[data]` represents the value at the memory location we wish to load from. First, we set `A` to 222222222. Next, we perform an `Opr` with `[data]`; this sets both `A` and `[data]` to the value previously in `[data]` but with the 1s and 2s swapped. Lastly, we do exactly the same thing again: Set `A` to 222222222 and perform another `Opr` with `[data]`. This swaps the 1s and 2s back and restores `[data]` to its original value. Afterwards, We are left with the desired data from `[data]` loaded into the `A` register [7].

Alternatively, we could perform a `Rot` 10 times on `[data]` and get the same result. However, this isn't nearly as efficient as the first method.

Synthesizing a store is much more complex due to the fact that we have to prepare the value at the destination address before we can store any data into it. Assume `[dest]` represents the value at the memory location we wish to store data into, and `data` represents the data we wish to store. Synthesizing a store can be done by doing the following:

1. Save the value of `A (data)` into a temporary memory location of which the value is `0t111111111` by performing an `Opr`. Note that this will swap the 0s and 1s in `data`.
2. Set `A` to `0t111111111` and perform an `Opr` with `[dest]`. `[dest]` now contains only 0s and 2s.
3. Set `A` to `0t222222222` and perform an `Opr` with `[dest]`. `[dest]` now contains only 0s and 1s.
4. Set `A` to `0t000000000` and perform an `Opr` with `[dest]`. `[dest]` now contains only 1s.
5. Retrieve `data` using the load method described earlier. The value of `data` is now loaded into `A`.
6. Perform an `Opr` with `[dest]`. `data` is now stored in `[dest]`.

Remember that `data` had its 0s and 1s swapped in step 1. Because `[dest]` contains all 1s after step 4, `data` gets restored in step 6 and thus the original value of `data` is stored in `[dest]` [7].

2.4. Implementing Arithmetic in Malbolge

Doing arithmetic in Malbolge is ridiculously complicated, as is with most things in this language. As you may have noticed, there are no arithmetic operations in Malbolge. Instead, we are given only two data-manipulation operations: `Opr` and `Rot`. Neither of these operations seem particularly useful when it comes to implementing arithmetic in Malbolge. However, it has been proven by exhaustive search [5] that you can build any operation using only `Opr` and `Rot`. For example, below is a function that will add two ternary values:

```
Opr(Opr(Opr(X,C0),Opr(C2,Opr(Y,C0))),Opr(C2,X))
```

Where `C0` = `0t000000000`, `C2` = `0t222222222`, and `X` and `Y` are the values you want to add together. Note that this function does not handle carries, so adding `0t0000000002` + `0t0000000001` will not work. Additionally, `Y` cannot contain any 2s.

Another method to do arithmetic in Malbolge is by table lookup. To do this, you would need a table filled with pre-computed values and an equally-sized array of jump targets.

3. Writing a Malbolge Program

When it comes to actually writing a program in Malbolge, we *could* make ourselves miserable and attempt to write straight in Malbolge, but why do that when we could write our program in a *Malbolge assembly language* instead?

3.1. Introducing the HeLL Assembly Language

HeLL (**H**ellish **L**ow-level **L**anguage) is one of two assembly languages that exist for Malbolge—the other being LaL (**L**ow-level **A**ssembly **L**anguage for Malbolge); LaL came first and was created by the same Japanese researchers who wrote the ‘99 bottles of beer’ program, and HeLL was created later in 2013 by Matthias Lutter. HeLL is based off of LaL and was created due to there being no precise specifications for LaL available to the public at the time (this has since changed) [1].

Writing Malbolge programs in a Malbolge assembly language like HeLL rather than directly in Malbolge makes the process slightly less torturous by adding a level of readability and writability to the language. HeLL introduces labels so that the programmer doesn’t have to use ternary addresses as references all the time. Additionally, HeLL uses mnemonics for pure Malbolge instructions (`Jump` instead of `i`, `In` instead of `/`, etc). See Appendix A for a list of every mnemonic.

The HeLL assembly language uses an assembler called LMAO (**L**ow-level **M**albolge **A**ssembler, **O**oh!) to build Malbolge programs from HeLL programs.

3.2. The LMAO Assembler

The LMAO assembler was created by Matthias Lutter alongside HeLL and does a few things for the convenience of the programmer.

LMAO decrements every reference by 1 automatically [1]. As I explained in section 2.1, when executing a `Jump`, the instruction itself is not encrypted—rather, the jump *target* is. By decrementing references by 1, LMAO is eliminating the need for us to accommodate Malbolge encrypting the instructions we intend to jump to.

LMAO also aids in memory initialization. If we want to write Malbolge programs that include conditional branches, loops, and input processing, it is necessary that we are able to initialize any desired memory cell in the Malbolge virtual machine to any desired value **on startup**. However, this is not possible in Malbolge. Thus, the first thing the LMAO assembler does is generate Malbolge code that does nothing else but write the required values to their corresponding memory cells [1].

Additionally, During the ‘memory initialization’ step, LMAO also initializes the `C` and `D` registers to point to specific values. `C` is initialized to point to a random `Jump` instruction and `D` is initialized to point to the data at a label called “ENTRY” that is required in every HeLL program (think of it as HeLL’s version of the *main function* found in languages like C and Java). `A` is also initialized during this step and is set to the value at `ENTRY - 1`; however, we shouldn’t rely on this behavior, so instead we consider `A` undefined until we write data to it [1].

3.3. Examining a HeLL Program

Please refer to the sample HeLL program featured in Appendix B throughout the following two sections. This program is a non-terminating cat program that copies its input to output.

I'd first like to point your attention to the labels `.CODE` and `.DATA`. Like I mentioned earlier, Malbolge stores its code and data together in the same memory. However, it makes sense that we would want to know which memory cells are used for code and which are used for data, so HeLL does something nice for us and uses these labels to distinguish between the two [1]. Note that the required `ENTRY` label must be in the `.DATA` section.

Next, you'll notice the prefix `R_` before some of the reference labels. Remember that LMAO decrements every reference by one. Adding this prefix before a reference label *adds* one to it and thus cancels out the decrement. For example, `R_MOVD` will cause the instruction at line 3 to be encrypted rather than the instruction before it (one we don't care about). We use this prefix when we want to progress to the next instruction in a cycle in a single step.

Lastly, the `?-` indicates a memory cell with undefined content [1]. We include these in our code when we are executing instructions that don't care about the value of `[D]`. Neither the `In` nor `Out` instructions use `[D]`, so we include the `?-`. Really, we could have anything in these spots, but we use `?-` to make the code more readable.

Now that you have a better understanding of the syntax of HeLL, let's walk through this cat program and see how it works.

3.4. Stepping Through a cat Program Written in HeLL

At the beginning of the program, `C` is pointing to a random `Jmp` instruction and `D` is pointing to `IN - 1` on line 16 (`- 1` because LMAO decrements all references by 1). When we step forward, `C` will then be pointing to the `In` instruction on line 7, and `D` will be pointing to the `?-` still on line 16. Another step forward and the `In` instruction will have been executed, taking a character from standard input and storing it in `A`. Now that we have our input, we want to restore the `In/Nop` cycle on line 7 so that the current instruction is back to being an `In`. In our next step, `C` jumps to `IN` (no `- 1` this time because of the `R_` prefix), encrypts the `Nop` back into an `In`, and is finally incremented back to pointing to the `Jmp` instruction on line 8.

Next we want to output the value in `A`. At this stage, `C` is pointing to the `Jmp` instruction on line 8, and `D` is pointing to `OUT - 1` on line 17. When we take a step, `C` will now be pointing to the `Out` instruction on line 11 and `D` will be pointing to another `?-`. Another step and the value in `A` will have been outputted to standard output. Like before, we want to restore our `Out/Nop` cycle on line 11, so `C` jumps to `OUT`, restores the cycle, and is left pointing to the `Jmp` instruction again on line 12.

Lastly, we want our program to loop and do the whole thing over again. You'll notice that the cycle on line 3 is a `Nop/MovD` instead of a `MovD/Nop`. This is because after the `MovD` is executed, `D` will be pointing to the data at `ENTRY`, which means we'll need to restore the cycle *before* we execute `MovD` so that it actually gets restored in every loop. Let's continue with the walkthrough: `C` is currently pointing to the `Jump` instruction on line 12 and `D` is pointing to `MOVD` on line 18. When we take a step, `C` will jump to the `Nop` on line 3, restore it to a `MovD`, then end at the `Jump` instruction on line 4. Another step and `C` is pointing to the `MovD` instruction on line 3. Finally, the next step will execute `MovD` and set `D` to point to `IN - 1` on line 16 again. The program has now been "reset" and is ready to do the whole thing over again.

4. A Program that Adds 1 to an ASCII Character

Appendix C features a Malbolge program I wrote using the HeLL assembly language. You can find its Malbolge representation in Appendix D. This program adds 1 to a user-inputted ASCII character, so 'a' -> 'b', '\$' -> '%', etc. However, the method I used to add doesn't handle carries, so it won't work for any character for which the ternary representation has a 2 in the 0th place (every third character).

To make this ASCII-adder, I used the function described earlier in section 2.4:

```
Opr(Opr(Opr(X,C0),Opr(C2,Opr(Y,C0))),Opr(C2,X))
```

Calculated in the following order:

1. `Opr(C2,X)`
2. `Opr(Y,C0)`
3. `Opr(C2,Opr(Y,C0))`
4. `Opr(X,C0)`
5. `Opr(Opr(X,C0),Opr(C2,Opr(Y,C0)))`
6. `Opr(Opr(Opr(X,C0),Opr(C2,Opr(Y,C0))),Opr(C2,X))`

Where `X` = user input and `Y` = 1. Enjoy!

References

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Appendix A

| Instruction | Mnemonic | Description | Pseudocode |
|-------------|----------|--|------------------------------|
| j | MovD | Set data pointer D to the value in [D] | D = [D] |
| i | Jmp | Set code pointer C to the value in [D] | C = [D] |
| * | Rot | Circularly shift the trit value in [D] to the right and store in A | A = [D] = Rot([D]) |
| p | Opr | Apply the “crazy” operation to [D] and A and store in A | A = [D] = Opr(A, [D]) |
| < | Out | Output the character in A , modulo 256, to standard output | print(A % 256) |
| / | In | Input a character from standard input and store in A | A = input |
| v | Hlt | Stop execution of the program | halt |
| o | Nop | No operation | Nop |

Appendix B

```

1.  .CODE
2.  MOVD:
3.      Nop/MovD
4.      Jmp
5.
6.  IN:
7.      In/Nop
8.      Jmp
9.
10. OUT:
11.     Out/Nop
12.     Jmp
13.
14. .DATA
15. ENTRY:
16.     IN ?- R_IN
17.     OUT ?- R_OUT
18.     R_MOVD MOVD ENTRY

```

Appendix C

```
1.  .CODE
2.  // standard malbolge commands
3.  MOVD:
4.      MovD/Nop
5.      Jmp
6.
7.  CRAZY:
8.      Opr/Nop
9.      Jmp
10.
11. ROT:
12.     Rot/Nop
13.     Jmp
14.
15. HALT:
16.     Hlt
17.
18. OUT:
19.     Out/Nop
20.     Jmp
21.
22. IN:
23.     In/Nop
24.     Jmp
25.
26. // the following routines act as 'counters'
27. COUNT:
28.     Nop/MovD
29.     Jmp
30.
31. COUNT2:
32.     Nop/Nop/MovD/Nop
33.     Jmp
34.
35. .DATA
36. // C1 = Opr(C2, input) on first run
37. // C1 = Opr(Opr(Opr(input, C0), Opr(C2, Opr(1, C0)))), Opr(C2, input))
38. // on second run
39. STEP1_6:
40.     CRAZY C1
41.     COUNT CONT2_5 // hit on first run
42.     COUNT2 CONT10 // hit on third run
```

```

43.          COUNT CONT3          // hit on second run
44.
45.  // C0 = Opr(1, C0) on first run
46.  // C0 = Opr(C2, Opr(1, C0)) on second run
47.  // C0 = Opr(Opr(input, C0), Opr(C2, Opr(1, C0))) on third run
48.  STEP2_3_5:
49.          CRAZY C0
50.          COUNT CONT4          // hit on first run
51.          COUNT2 CONT9         // hit on third run
52.          COUNT CONT5         // hit on second run
53.
54.  // C0 = Opr(input, C0)
55.  STEP4:
56.          CRAZY C0
57.          COUNT CONT8
58.
59.  // C1 = input
60.  STORE_INPUT:
61.          CRAZY C1
62.          COUNT CONT2          // hit on first run
63.          COUNT2 CONT7         // hit on third run
64.          COUNT CONT6         // hit on second run
65.
66.  GET_INPUT:
67.          IN ?-
68.          R_MOVD MOVD CONT1
69.
70.  // This section is responsible for the general "flow" of the program
71.  ENTRY:
72.          MOVD GET_INPUT
73.
74.  CONT1:
75.          CRAZY C1 R_CRAZY // prepare input to store
76.          R_COUNT
77.          R_MOVD MOVD STORE_INPUT
78.
79.  CONT2:
80.          R_CRAZY
81.          R_COUNT
82.          CRAZY C1 R_CRAZY // prepare input to store
83.          R_MOVD MOVD STEP1_6
84.
85.  CONT2_5:
86.          ROT C2

```

```

87.      R_CRAZY
88.      R_MOVD MOVD STEP1_6
89.
90.  CONT3:
91.      R_COUNT2 R_COUNT2 R_COUNT2
92.      R_ROT ROT 3          // put 1 in A
93.      R_CRAZY
94.      R_COUNT
95.      R_MOVD MOVD STEP2_3_5
96.
97.  CONT4:
98.      R_ROT ROT C2
99.      R_CRAZY
100.     R_MOVD MOVD STEP2_3_5
101.
102.  CONT5:
103.     R_ROT ROT C2
104.     R_CRAZY
105.     R_MOVD MOVD STORE_INPUT
106.
107.  CONT6:
108.     R_ROT ROT C2
109.     R_CRAZY
110.     R_MOVD MOVD STORE_INPUT
111.
112.  CONT7:
113.     R_CRAZY
114.     R_MOVD MOVD STEP4
115.
116.  CONT8:
117.     R_CRAZY
118.     R_COUNT2 R_COUNT2 R_COUNT2
119.     R_MOVD MOVD STEP2_3_5
120.
121.  CONT9:
122.     R_CRAZY
123.     R_COUNT
124.     R_COUNT2 R_COUNT2 R_COUNT2
125.     R_MOVD MOVD STEP1_6
126.
127.  CONT10:
128.     OUT ?-
129.     R_ROT ROT 30          //print newline after char
130.     R_OUT OUT ?- HALT

```

Appendix D

bP&A@?>=<;:9876543210/.-,+)('&%"T"!~}|;]yxwvutslUSRQ.yx+i)J9edFb4`_^]\yxwRQ)(TSRQ]m!G0
KJIyxFvDa%_@?"=<5:98765.-2+*/.-,+)('&%"\$#!~}|utyrvutsrqjonmPkjihgfedc\DDYAA\>>Y;;V886
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;_]\=IH{j21x/S-2>Np.o,I1)"i~Veez@a_*tyr8YYtVEDj|/-,eji(ts&dG"[m]X@z=YRQ)sr&L\$4\H1}j-h
He@R' '%;:po=}|X9z7UfRucsq)p:, \kG5hD%UTdc-,v_z]xw7YG43110QP1>Mv(K9e\$#\a3~^jz[gY;d:b7SpQo
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