BombLab 实验报告

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一、文件/工具

- bomb38
- bomb.c
- gdb

二、准备工作

1. 生成反汇编文件

执行：

```
objdump-d bomb38 > bomb38.asm
```

获得反汇编文件bomb38.asm，便于整体阅读。

2. 阅读`bomb.c`

```
// ......
    else if (argc == 2) {
    if (!(infile = fopen(argv[1], "r"))) {
        printf("%s: Error: Couldn't open %s\n", argv[0], argv[1]);
        exit(8);
    }
    }
    // ......
    /* Hmm...  Six phases must be more secure than one phase! */
    input = read_line();             /* Get input                   */
    phase_1(input);                  /* Run the phase               */
    phase_defused();                 /* Drat!  They figured it out!
                      * Let me know how they did it. */
    printf("Phase 1 defused. How about the next one?\n");

    // ......

    /* Wow, they got it!  But isn't something... missing?  Perhaps
     * something they overlooked?  Mua ha ha ha ha! */
// ......
```

通过阅读`bomb.c`，可以知道拆弹过程共分7阶段，phase_1~6以及最后的隐藏阶段。每一阶段系统从输入中读一行字符串，输入可以是标准输入`stdin`或从命令行参数中指定的文件中获得。我们在程序目录下新建一个文本文档`solution.txt`作为运行时的命令行参数，每解开一阶段，将该阶段的答案追加到其中。注意，将每一题的答案写入solution.txt后，行尾需要有一个换行符。

3. 用到的C库函数

本次实验中用到的不熟悉的C库函数有`sscanf`和`strtol`。

- `sscanf`

  声明

  ```
  int sscanf(const char *str, const char *format, ...)
  ```

  参数

  `sscanf`与`scanf`相似，只是`scanf`的字符串源为标准输入，而`sscanf`的字符串源是传入的第一个参数`str`。

  第二个参数为解读格式，后面的附加参数即为解读后的变量要存储的地址。

  返回值

  如果成功，该函数返回成功匹配和赋值的个数，否则返回`EOF`。

- `strtol`（即string to long）

  声明

  ```
  long strtol(const char *str, char **endptr, int base)
  ```

  参数

  `str`为要转换成`long`类型的字符串，`endptr`的值由函数指向`str`中有效数字后的下一个字符（如果字符串是纯数字`*endptr == '\0'`），`base`决定把`str`转为几进制。

  返回值

  返回转换成的`long`类型值。如果输入字符串不是纯数字，返回`0`。

4. 约定

把寄存器`%rdi`,`%rsi`,...中存放的变量依次称为`arg1`,`arg2`,...。

三、实验过程

phase_1

```
00000000000015e7 <phase_1>:
    15e7:   f3 0f 1e fa             endbr64
    15eb:   48 83 ec 08             sub    $0x8,%rsp               # 维护栈帧
    15ef:   48 8d 35 5a 1b 00 00    lea    0x1b5a(%rip),%rsi        # 3150 <_IO_stdin_used+0x150>    # arg2 = 0x3150
    15f6:   e8 f8 04 00 00          callq  1af3 <strings_not_equal> # 调用strings_not_equal函数
    15fb:   85 c0                   test   %eax,%eax
    15fd:   75 05                   jne    1604 <phase_1+0x1d>       # 要求字符串相同，否则爆炸
    15ff:   48 83 c4 08             add    $0x8,%rsp               # 回收栈帧
    1603:   c3                      retq
    1604:   e8 fe 05 00 00          callq  1c07 <explode_bomb>
    1609:   eb f4                   jmp    15ff <phase_1+0x18>
```

- `sub   $0x8,%rsp`和`add   $0x8,%rsp`的操作是在给`phase_1()`函数维护一个独立的栈帧，以后每一阶段都会出现类似的代码。
- 简单看函数`strings_not_equal(arg1, arg2)`的反汇编代码，它返回命题`字符串*arg1与*arg2相同`的布尔值。
- `15ef`处把地址`0x3150`（**注**. 这是虚拟地址、相对地址，该地址在程序运行时会重定向到真实物理内存地址）赋给了`arg2`，只有当我们的输入字符串（即`*arg1`）与`*arg2`相同才不会爆炸。

所以我们要输入地址`0x3150`中存放的字符串。输入`gdb bomb38`进入gdb调试程序`bomb38`（尚不运行），输入`x/s 0x3150`得到字符串为`"Border relations with Canada have never been better."`。

phase_2

```
000000000000160b <phase_2>:
    160b:	f3 0f 1e fa          	endbr64 
    160f:	55                   	push   %rbp
    1610:	53                   	push   %rbx                 # callee保存寄存器
    1611:	48 83 ec 28          	sub    $0x28,%rsp
    1615:	64 48 8b 04 25 28 00 	mov    %fs:0x28,%rax        # 用于栈溢出保护
    161c:	00 00 
    161e:	48 89 44 24 18       	mov    %rax,0x18(%rsp)
    1623:	31 c0                	xor    %eax,%eax            # 返回值置0
    1625:	48 89 e6             	mov    %rsp,%rsi            # arg2 = 栈顶
    1628:	e8 06 06 00 00       	callq  1c33 <read_six_numbers>   # 调用
read_six_numbers
    162d:	83 3c 24 00          	cmpl   $0x0,(%rsp)
    1631:	78 0a                	js     163d <phase_2+0x32>  # 要求num1 >= 0

 # 1633 - 165f: 循环结构
    1633:	48 89 e5             	mov    %rsp,%rbp            # rbp = 当前栈顶
    1636:	bb 01 00 00 00       	mov    $0x1,%ebx            # ebx = 1
    163b:	eb 13                	jmp    1650 <phase_2+0x415> # goto .L1
    163d:	e8 c5 05 00 00       	callq  1c07 <explode_bomb>
    1642:	eb ef                	jmp    1633 <phase_2+0x28>
.Loop:
    1644:	83 c3 01             	add    $0x1,%ebx            # ebx += 1
    1647:	48 83 c5 04          	add    $0x4,%rbp            # rbp += 4
    164b:	83 fb 06             	cmp    $0x6,%ebx
    164e:	74 11                	je     1661 <phase_2+0x56>  # if ebx == 6, 成
功
.L1:
    1650:	89 d8                	mov    %ebx,%eax            # 返回值 = ebx
    1652:	03 45 00             	add    0x0(%rbp),%eax       # 返回值 += *(rbp)
    1655:	39 45 04             	cmp    %eax,0x4(%rbp)
    1658:	74 ea                	je     1644 <phase_2+0x39>  # 要求返回值 == *
(rbp+4), goto .Loop
    165a:	e8 a8 05 00 00       	callq  1c07 <explode_bomb>
    165f:	eb e3                	jmp    1644 <phase_2+0x39>

    1661:	48 8b 44 24 18       	mov    0x18(%rsp),%rax
    1666:	64 48 2b 04 25 28 00 	sub    %fs:0x28,%rax
    166d:	00 00 
    166f:	75 07                	jne    1678 <phase_2+0x6d>
    1671:	48 83 c4 28          	add    $0x28,%rsp
    1675:	5b                   	pop    %rbx
    1676:	5d                   	pop    %rbp
    1677:	c3                   	retq   
    1678:	e8 d3 fb ff ff       	callq  1250 <__stack_chk_fail@plt>

0000000000001c33 <read_six_numbers>:                       # 被phase_2调用时，arg1
= 我们输入，arg2 = 栈顶位置
    1c33:	f3 0f 1e fa          	endbr64 
    1c37:	48 83 ec 08          	sub    $0x8,%rsp
    1c3b:	48 89 f2             	mov    %rsi,%rdx         # arg3 = 栈顶
    1c3e:	48 8d 4e 04          	lea    0x4(%rsi),%rcx    # arg4 = 栈顶+4
    1c42:	48 8d 46 14          	lea    0x14(%rsi),%rax  # 返回值 = 栈顶+20
    1c46:	50                   	push   %rax              # 返回值压入栈
    1c47:	48 8d 46 10          	lea    0x10(%rsi),%rax  # 返回值 = 栈顶+16
    1c4b:	50                   	push   %rax              # 返回值压入栈
    1c4c:	4c 8d 4e 0c          	lea    0xc(%rsi),%r9     # arg6 = 栈顶+12
    1c50:	4c 8d 46 08          	lea    0x8(%rsi),%r8     # arg5 = 栈顶+8
    1c54:	48 8d 35 c8 16 00 00 	lea    0x16c8(%rip),%rsi# 3323
<array.0+0x143>
                                                           # arg2 = 0x3323,
*arg2="%d %d %d %d %d %d"
    1c5b:	b8 00 00 00 00       	mov    $0x0,%eax         # 返回值置0
    1c60:	e8 9b f6 ff ff       	callq  1300 <__isoc99_sscanf@plt>
    1c65:	48 83 c4 10          	add    $0x10,%rsp
    1c69:	83 f8 05             	cmp    $0x5,%eax
    1c6c:	7e 05                	jle    1c73 <read_six_numbers+0x40> # 要求返回
值>=6，即要读出6个数字
    1c6e:	48 83 c4 08          	add    $0x8,%rsp
    1c72:	c3                   	retq   
    1c73:	e8 8f ff ff ff       	callq  1c07 <explode_bomb>
```

- `push  %rbp` 是因为 `%rbp` 为被调用者保存寄存器； `mov  %fs:0x28,%rax` 等代码是用于处理栈溢出异常。以后每一阶段都会出现类似的代码。
- `read_six_numbers()` 中，通过 `x/s 0x3323` 可以得到 `arg2` 为 `%d %d %d %d %d %d`。 `sscanf()` 需要8个参数才能从我们输入的字符串中读取6个数字，而寄存器最多只能传输6个参数，因此第7，8个参数， `栈顶+16` 和 `栈顶+20` 要分别压入栈。

也就是说，从我们输入的字符串读取的六个数字被依次存放进了 `栈顶` ~ `栈顶+20` 位置（每个数字占4字节），我们把其中存放的数字分别记为 `num1` ~ `num6`。

`1633` ~ `165f` 为循环结构，其整体逻辑如下

```
(rbp) = num1, ebx = 1
while ebx != 6:
    if ebx + (rbp) != 下一个数字
        爆炸
    ebx ++, (rbp) = 下一个数字
```

所以我们得到要求：

$$\begin{gathered}num1 \geq 0, \\ num2 = num1 + 1, \\ num3 = num2 + 2, \\ \dots \\ num6 = num5 + 5\end{gathered}$$

序列如`1,2,4,7,11,16`即满足要求。

phase_3

```
000000000000167d <phase_3>:
    167d:	f3 0f 1e fa          	endbr64 
    1681:	48 83 ec 18          	sub    $0x18,%rsp
    1685:	64 48 8b 04 25 28 00 	mov    %fs:0x28,%rax
    168c:	00 00 
    168e:	48 89 44 24 08       	mov    %rax,0x8(%rsp)
    1693:	31 c0                	xor    %eax,%eax
    1695:	48 8d 4c 24 04       	lea    0x4(%rsp),%rcx          # arg4 = 栈顶+4
    169a:	48 89 e2             	mov    %rsp,%rdx               # arg3 = 栈顶
    169d:	48 8d 35 8b 1c 00 00 	lea    0x1c8b(%rip),%rsi        # 332f <array.0+0x14f>
                                                                # *arg2 = "%d %d"
    16a4:	e8 57 fc ff ff       	callq  1300 <__isoc99_sscanf@plt>
    16a9:	83 f8 01             	cmp    $0x1,%eax
    16ac:	7e 1a                	jle    16c8 <phase_3+0x4b>      # 确保有两个数
                                                                # num1存在栈顶，num2存在栈顶+4
    16ae:	83 3c 24 07          	cmpl   $0x7,(%rsp)
    16b2:	77 65                	ja     1719 <phase_3+0x9c>      # 要求0 <= num1 <= 7(ja提示了元素类型)
    16b4:	8b 04 24             	mov    (%rsp),%eax             # 返回值 = num1
    16b7:	48 8d 15 02 1b 00 00 	lea    0x1b02(%rip),%rdx        # 31c0 <_IO_stdin_used+0x1c0>
                                                                # arg3 = 0x31c0
    16be:	48 63 04 82          	movslq (%rdx,%rax,4),%rax
    16c2:	48 01 d0             	add    %rdx,%rax               # 返回值 = M[arg3 + 4*num1] + arg3
    16c5:	3e ff e0             	notrack jmpq *%rax            # 跳转到M[arg3 + 4*返回值] + arg3
                                                                # 猜测为16ef后面的分支 8个分支对应num1的0-7

    16c8:	e8 3a 05 00 00       	callq  1c07 <explode_bomb>

    16cd:	eb df                	jmp    16ae <phase_3+0x31>      # 无入口
    16cf:	b8 5a 02 00 00       	mov    $0x25a,%eax             # 无入口

# 出口
    16d4:	39 44 24 04          	cmp    %eax,0x4(%rsp)
    16d8:   75 52                   jne    172c <phase_3+0xaf>      # 要求num2 = 
返回值
    16da:   48 8b 44 24 08          mov    0x8(%rsp),%rax
    16df:   64 48 2b 04 25 28 00    sub    %fs:0x28,%rax
    16e6:   00 00 
    16e8:   75 49                   jne    1733 <phase_3+0xb6>
    16ea:   48 83 c4 18             add    $0x18,%rsp
    16ee:   c3                      retq   
# 八条分支对应num1的0-7
    16ef:   b8 a0 02 00 00          mov    $0x2a0,%eax
    16f4:   eb de                   jmp    16d4 <phase_3+0x57>
    16f6:   b8 42 01 00 00          mov    $0x142,%eax
    16fb:   eb d7                   jmp    16d4 <phase_3+0x57>
    16fd:   b8 83 02 00 00          mov    $0x283,%eax
    1702:   eb d0                   jmp    16d4 <phase_3+0x57>
    1704:   b8 3b 01 00 00          mov    $0x13b,%eax
    1709:   eb c9                   jmp    16d4 <phase_3+0x57>
    170b:   b8 7f 03 00 00          mov    $0x37f,%eax              # 对应num1 = 6
    1710:   eb c2                   jmp    16d4 <phase_3+0x57>
    1712:   b8 7a 02 00 00          mov    $0x27a,%eax
    1717:   eb bb                   jmp    16d4 <phase_3+0x57>

    1719:   e8 e9 04 00 00          callq  1c07 <explode_bomb>

    171e:   b8 00 00 00 00          mov    $0x0,%eax
    1723:   eb af                   jmp    16d4 <phase_3+0x57>
    1725:   b8 52 02 00 00          mov    $0x252,%eax
    172a:   eb a8                   jmp    16d4 <phase_3+0x57>

    172c:   e8 d6 04 00 00          callq  1c07 <explode_bomb>
    1731:   eb a7                   jmp    16da <phase_3+0x5d>
    1733:   e8 18 fb ff ff          callq  1250 <__stack_chk_fail@plt>
```

阅读代码，我们可以推断出

- `0 <= num1 <=7`。
- `16c5 notrack jmpq *%rax` 跳转到 `M[arg3 + 4*num1] + arg3`，猜测为 `16ef` 后面的分支 8个分支对应 `num1 = 0~7`，这8个分支会各自改变 `返回值`，然后跳转到判断 `num2` 是否等于 `返回值`。（`arg3 = 0x31c0`）
- `num2 = 返回值` 则拆弹成功。

那我们可以随意代入一个 `num1 = 6`，算出 `arg3 + 4*num1 = 0x31d8`，用gdb查看 `x/xw 0x31d8` 得到 `0xffffe54b`，为 `0x1ab5` 的相反数（先-1后取反），则会跳转到 `0x31c0 - 0x1ab5 = 0x170b` 处，`返回值 = 0x37f`，即 `num2 = 895`。

所以一个答案为 `6 895`。

phase_4

```
000000000000176e <phase_4>:
    176e:   f3 0f 1e fa             endbr64 
    1772:   48 83 ec 18             sub    $0x18,%rsp
    1776:   64 48 8b 04 25 28 00    mov    %fs:0x28,%rax
    177d:   00 00 
    177f:	48 89 44 24 08       	mov    %rax,0x8(%rsp)
    1784:	31 c0                	xor    %eax,%eax
    1786:	48 8d 4c 24 04       	lea    0x4(%rsp),%rcx         # arg4 = 栈顶+4
    178b:	48 89 e2             	mov    %rsp,%rdx              # arg3 = 栈顶
    178e:	48 8d 35 9a 1b 00 00 	lea    0x1b9a(%rip),%rsi      # 332f <array.0+0x14f>
                                                              # *arg2 = "%d %d"
    1795:	e8 66 fb ff ff       	callq  1300 <__isoc99_sscanf@plt>
    179a:	83 f8 02             	cmp    $0x2,%eax
    179d:	75 06                	jne    17a5 <phase_4+0x37>    # 确保有两个数
                                                              # num1存在栈顶，num2存在栈顶+4
    179f:	83 3c 24 0e          	cmpl   $0xe,(%rsp)
    17a3:	76 05                	jbe    17aa <phase_4+0x3c>    # 要求0 <= num1 <= 14
    17a5:	e8 5d 04 00 00       	callq  1c07 <explode_bomb>
    17aa:	ba 0e 00 00 00       	mov    $0xe,%edx              # arg3 = 14
    17af:	be 00 00 00 00       	mov    $0x0,%esi              # arg2 = 0
    17b4:	8b 3c 24             	mov    (%rsp),%edi            # arg1 = num1
    17b7:	e8 7c ff ff ff       	callq  1738 <func4>           # 调用func4()
    17bc:	83 f8 13             	cmp    $0x13,%eax
    17bf:	75 07                	jne    17c8 <phase_4+0x5a>    # 要求返回值 = 19
    17c1:	83 7c 24 04 13       	cmpl   $0x13,0x4(%rsp)
    17c6:	74 05                	je     17cd <phase_4+0x5f>    # 要求num2 = 19(已解决)
    17c8:	e8 3a 04 00 00       	callq  1c07 <explode_bomb>
    17cd:	48 8b 44 24 08       	mov    0x8(%rsp),%rax
    17d2:	64 48 2b 04 25 28 00 	sub    %fs:0x28,%rax
    17d9:	00 00 
    17db:	75 05                	jne    17e2 <phase_4+0x74>
    17dd:	48 83 c4 18          	add    $0x18,%rsp
    17e1:	c3                   	retq   
    17e2:	e8 69 fa ff ff       	callq  1250 <__stack_chk_fail@plt>
```

阅读代码，可以推断出：

- `0 <= num1 <= 14`且`func4(num1, 0, 14) = 19`。
- `num2 = 19`。

那么只需要解出方程`func4(num1, 0, 14) = 19, 0 <= num1 <= 14`即可。

```
0000000000001738 <func4>:                                 # func4(arg1, arg2, arg3)
    1738:	f3 0f 1e fa          	endbr64 
    173c:	53                   	push   %rbx
    173d:	89 d0                	mov    %edx,%eax
    173f:	29 f0                	sub    %esi,%eax          # 返回值 = arg3 - arg2
    1741:	89 c3                	mov    %eax,%ebx          # ebx = arg3 - arg2
    1743:   c1 eb 1f                shr    $0x1f,%ebx              # 逻辑右移 ebx>>=
31，就是取符号位，0或-1
    1746:   01 c3                   add    %eax,%ebx               # ebx += arg3 -
arg2
    1748:   d1 fb                   sar    %ebx                    # 默认第二个操作数是
1
    174a:   01 f3                   add    %esi,%ebx
                                    # 最终，ebx = 1/2 * [arg3 - arg2 + 符号(0/-1)]
+ arg2
    174c:   39 fb                   cmp    %edi,%ebx
    174e:   7f 06                   jg     1756 <func4+0x1e>       # if ebx > arg1
    1750:   7c 10                   jl     1762 <func4+0x2a>       # if ebx < arg1
# if %ebx = arg1（递归出口）
    1752:   89 d8                   mov    %ebx,%eax               # 返回值 = rbx
    1754:   5b                      pop    %rbx                    # 恢复被调用者保存寄
存器
    1755:   c3                      retq
# if %ebx > arg1
    1756:   8d 53 ff                lea    -0x1(%rbx),%edx         # arg3 = rbx-1
    1759:   e8 da ff ff ff          callq  1738 <func4>            # fun4()
    175e:   01 c3                   add    %eax,%ebx               # rbx = rbx + 返回
值
    1760:   eb f0                   jmp    1752 <func4+0x1a>       # 跳到递归出口
# if %ebx < arg1
    1762:   8d 73 01                lea    0x1(%rbx),%esi          # arg2 = rbx+1
    1765:   e8 ce ff ff ff          callq  1738 <func4>            # fun4()
    176a:   01 c3                   add    %eax,%ebx               # rbx = rbx + 返回
值
    176c:   eb e4                   jmp    1752 <func4+0x1a>       # 跳到递归出库
```

直接写出C代码，用程序枚举求解方程。

```c
#include <stdio.h>

int func4(int arg1, int arg2, int arg3){
    int ebx;
    ebx = arg3 - arg2 + (arg3>=arg2 ? 0 : -1);
    ebx = (unsigned) ebx;
    ebx >>= 1;
    ebx = (int) ebx;
    ebx += arg2;
    if(ebx > arg1){
        arg3 = ebx -1;
        ebx += func4(arg1, arg2, arg3);
        return ebx;
    }else if(ebx < arg1){
        arg2 = ebx + 1;
        ebx += func4(arg1, arg2, arg3);
        return ebx;
    }else{
        return ebx;
    }
}
```

```
int main(){
    // 求解方程func4(x, 0, 14) = 19, 0 <= x <= 14
    for(int x=0; x<=14; x++)
        if(func4(x, 0, 14) == 19)
            printf("Num1 = %d found.\n", x);
    return 0;
}
```

解得`num1 = 4`。故答案为`4 19`。

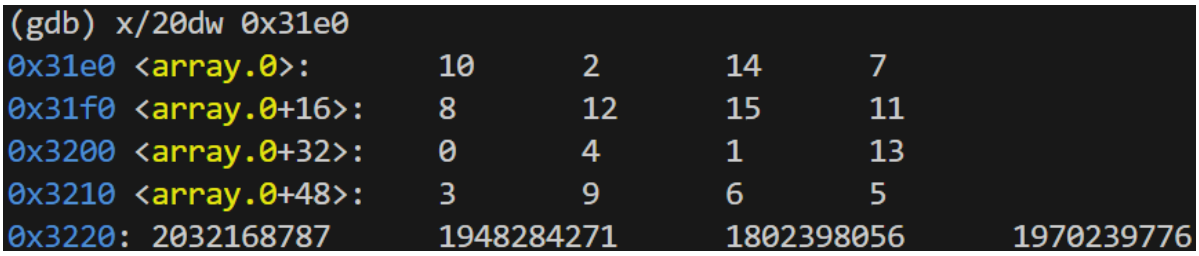
phase_5

```
00000000000017e7 <phase_5>:
    17e7:	f3 0f 1e fa          	endbr64 
    17eb:	48 83 ec 18          	sub    $0x18,%rsp
    17ef:	64 48 8b 04 25 28 00 	mov    %fs:0x28,%rax
    17f6:	00 00 
    17f8:	48 89 44 24 08       	mov    %rax,0x8(%rsp)
    17fd:	31 c0                	xor    %eax,%eax
    17ff:	48 8d 4c 24 04       	lea    0x4(%rsp),%rcx          # arg4 = 栈顶
地址+4
    1804:	48 89 e2             	mov    %rsp,%rdx               # arg3 = 栈顶
地址
    1807:	48 8d 35 21 1b 00 00 	lea    0x1b21(%rip),%rsi        # 332f
<array.0+0x14f>
                                                                # *arg2 = "%d
%d"
    180e:	e8 ed fa ff ff       	callq  1300 <__isoc99_sscanf@plt>
    1813:	83 f8 01             	cmp    $0x1,%eax
    1816:	7e 5a                	jle    1872 <phase_5+0x8b>      # 确认输入了两
个数
                                                                # num1存在栈
顶，num2存在栈顶+4
    1818:	8b 04 24             	mov    (%rsp),%eax             # 返回值 =
num1
    181b:	83 e0 0f             	and    $0xf,%eax               # 返回值做
&0b1111（保留低4位）
    181e:	89 04 24             	mov    %eax,(%rsp)             # 返回值放进栈
顶，即num1= 返回值 = num1后四位
    1821:	83 f8 0f             	cmp    $0xf,%eax
    1824:	74 32                	je     1858 <phase_5+0x71>      # num1不能是
0b1111即15
    1826:	b9 00 00 00 00       	mov    $0x0,%ecx
    182b:	ba 00 00 00 00       	mov    $0x0,%edx               # arg3, 4清空
    1830:	48 8d 35 a9 19 00 00 	lea    0x19a9(%rip),%rsi        # 31e0
<array.0>
                                                                # arg2 =
0x31e0, 是一个数组的首地址
# 循环
    1837:	83 c2 01             	add    $0x1,%edx             # arg3 += 1
    183a:	48 98                	cltq                         # 对%eax做符号扩
展，可无视
    183c:	8b 04 86             	mov    (%rsi,%rax,4),%eax    # 返回值 = M[arg2
+ 4 * %rax] = arr[返回值]
    183f:	01 c1                	add    %eax,%ecx             # arg4 += 返回值
    1841:	83 f8 0f             	cmp    $0xf,%eax
    1844:	75 f1                	jne    1837 <phase_5+0x50>  # 循环直到返回值 = 
0b1111 = 15 => 倒推!

    1846:	c7 04 24 0f 00 00 00 	movl   $0xf,(%rsp)          # 栈顶存0b1111
    184d:	83 fa 0f             	cmp    $0xf,%edx
    1850:	75 06                	jne    1858 <phase_5+0x71>  # 要求arg3 = 
0b1111 = 15, 即循环做15次
    1852:	39 4c 24 04          	cmp    %ecx,0x4(%rsp)
    1856:	74 05                	je     185d <phase_5+0x76>  # 要求num2 = arg4
    1858:	e8 aa 03 00 00       	callq  1c07 <explode_bomb>
    185d:	48 8b 44 24 08       	mov    0x8(%rsp),%rax
    1862:	64 48 2b 04 25 28 00 	sub    %fs:0x28,%rax
    1869:	00 00 
    186b:	75 0c                	jne    1879 <phase_5+0x92>
    186d:	48 83 c4 18          	add    $0x18,%rsp
    1871:	c3                   	retq   
    1872:	e8 90 03 00 00       	callq  1c07 <explode_bomb>
    1877:	eb 9f                	jmp    1818 <phase_5+0x31>
    1879:	e8 d2 f9 ff ff       	callq  1250 <__stack_chk_fail@plt>
```

阅读代码，可以推断出：

- `num1`会被做取余15操作，因此`num1`只需要从`0-14`中选择。
- `arg2`指向了一个数组`arr`的首地址，这个数组十分重要。代码从数组 `arr` 中根据初始下标 `num1` 开始遍历，并通过循环多次访问数组——**每次访问的下标是上一次访问的结果**。并要求：
  - 访问了**15**次。
  - 最后一次访问数组的**值为15**。
  - 对所有次访问，被访问元素的**累积**的值 `arg4` 等于 `num2`。
  - `num1`为第一次访问的**下标**。

访问`0x31e0`周围的内存，得到`arr`的信息：



```
(gdb) x/20dw 0x31e0
0x31e0 <array.0>:       10         2          14         7
0x31f0 <array.0+16>:    8          12         15         11
0x3200 <array.0+32>:    0          4          1          13
0x3210 <array.0+48>:    3          9          6          5
0x3220: 2032168787      1948284271      1802398056      1970239776
```

下标与数据的对应关系为：

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

逆推数组的访问过程，得到表格：

访问次数	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
访问下标	6	14	2	1	10	0	8	4	9	13	11	7	3	12	5
访问元素	15	6	14	2	1	10	0	8	4	9	13	11	7	3	12

所以`num1 = 5`，`num2 = Σ(访问元素) = 115`，即答案为`5 115`。

phase_6

```
000000000000187e <phase_6>:
    187e:   f3 0f 1e fa             endbr64
    1882:   41 56                   push   %r14
    1884:   41 55                   push   %r13
    1886:   41 54                   push   %r12
    1888:   55                      push   %rbp
    1889:   53                      push   %rbx
    188a:   48 83 ec 60             sub    $0x60,%rsp
    188e:   64 48 8b 04 25 28 00    mov    %fs:0x28,%rax
    1895:   00 00
    1897:   48 89 44 24 58          mov    %rax,0x58(%rsp)
    189c:   31 c0                   xor    %eax,%eax

    189e:   49 89 e5                mov    %rsp,%r13                # %r13 = 栈顶
位置，用于做迭代
    18a1:   4c 89 ee                mov    %r13,%rsi                # arg2 = 栈顶
位置，用于做参数
    18a4:   e8 8a 03 00 00          callq  1c33 <read_six_numbers>  # 读6个数字，依
次放入栈，依次记为 num1,...
    18a9:   41 be 01 00 00 00       mov    $0x1,%r14d               # %r14 = 1
    18af:   49 89 e4                mov    %rsp,%r12                # %r12 = 栈顶
位置，用于做基址
    18b2:   eb 28                   jmp    18dc <phase_6+0x5e>      # goto 入口
    18b4:   e8 4e 03 00 00          callq  1c07 <explode_bomb>
    18b9:   eb 30                   jmp    18eb <phase_6+0x6d>

    18bb:   48 83 c3 01             add    $0x1,%rbx                # rbx ++
    18bf:   83 fb 05                cmp    $0x5,%ebx
    18c2:   7f 10                   jg     18d4 <phase_6+0x56>      # if rbx >= 6
# L1
    18c4:   41 8b 04 9c             mov    (%r12,%rbx,4),%eax       # 返回值 =
M[r12+4*rbx] = num_(rbx+1)
    18c8:   39 45 00                cmp    %eax,0x0(%rbp)
    18cb:   75 ee                   jne    18bb <phase_6+0x3d>      # 要求num_i!=
返回值  => num_i互不相同
```

```
    18cd:   e8 35 03 00 00          callq  1c07 <explode_bomb>
    18d2:   eb e7                   jmp    18bb <phase_6+0x3d>

    18d4:   49 83 c6 01             add    $0x1,%r14               # r14 ++
    18d8:   49 83 c5 04             add    $0x4,%r13               # r13移向下一个
num
# 入口
    18dc:   4c 89 ed                mov    %r13,%rbp               # %rbp = %r13
    18df:   41 8b 45 00             mov    0x0(%r13),%eax
    18e3:   83 e8 01                sub    $0x1,%eax               # 返回值 =
num_i - 1
    18e6:   83 f8 05                cmp    $0x5,%eax
    18e9:   77 c9                   ja     18b4 <phase_6+0x36>     # 要求0 <=
num_i - 1 <= 5 => num_i∈[1,6]
    18eb:   41 83 fe 05             cmp    $0x5,%r14d
    18ef:   7f 05                   jg     18f6 <phase_6+0x78>     # if r14 >= 6
    18f1:   4c 89 f3                mov    %r14,%rbx               # rbx = r14
    18f4:   eb ce                   jmp    18c4 <phase_6+0x46>     # goto L1

# -------------------------------------------------------------

    18f6:   be 00 00 00 00          mov    $0x0,%esi               # arg2 = 0
# loop:
    18fb:   8b 0c b4                mov    (%rsp,%rsi,4),%ecx      # arg4 =
M[rsp+4*arg2] = num_(arg2+1)
    18fe:   b8 01 00 00 00          mov    $0x1,%eax               # 返回值 = 1
    1903:   48 8d 15 06 39 00 00    lea    0x3906(%rip),%rdx       # 5210
<node1>  # 让arg3指向第一个node
    190a:   83 f9 01                cmp    $0x1,%ecx
    190d:   7e 0b                   jle    191a <phase_6+0x9c>     # if
num_(arg2+1) <= 1, 即为最小的（1）
                                                                   # else
    190f:   48 8b 52 08             mov    0x8(%rdx),%rdx          # arg3 指向下
一个node
    1913:   83 c0 01                add    $0x1,%eax               # 返回值 += 1
    1916:   39 c8                   cmp    %ecx,%eax
    1918:   75 f5                   jne    190f <phase_6+0x91>     # if 返回值 !=
num_(arg2+1)
# if num_(arg2+1)是最小的（1）
    191a:   48 89 54 f4 20          mov    %rdx,0x20(%rsp,%rsi,8)  #
M[rsp+8*arg2+32] = arg3
    191f:   48 83 c6 01             add    $0x1,%rsi               # arg2 += 1
    1923:   48 83 fe 06             cmp    $0x6,%rsi
    1927:   75 d2                   jne    18fb <phase_6+0x7d>     # if arg2 !=
6, goto loop

# -------------------------------------------------------------

    1929:   48 8b 5c 24 20          mov    0x20(%rsp),%rbx         # rbx = 栈[栈
顶+32] = node_num1
    192e:   48 8b 44 24 28          mov    0x28(%rsp),%rax         # rax = 栈[栈
顶+40] = node_num2
    1933:   48 89 43 08             mov    %rax,0x8(%rbx)          #
node_num1.nextNode = node_num2
    1937:   48 8b 54 24 30          mov    0x30(%rsp),%rdx         # arg3 = 栈[栈
顶+48]
```

```
    193c:   48 89 50 08             mov    %rdx,0x8(%rax)            # M[返回值+8] = arg3
    1940:   48 8b 44 24 38          mov    0x38(%rsp),%rax           # 返回值 = 栈[栈顶+56]
    1945:   48 89 42 08             mov    %rax,0x8(%rdx)            # M[arg3+8] = 返回值
    1949:   48 8b 54 24 40          mov    0x40(%rsp),%rdx           # arg3 = 栈[栈顶+64]
    194e:   48 89 50 08             mov    %rdx,0x8(%rax)            # M[返回值+8] = arg3
    1952:   48 8b 44 24 48          mov    0x48(%rsp),%rax           # 返回值 = 栈[栈顶+72]
    1957:   48 89 42 08             mov    %rax,0x8(%rdx)            # M[arg3+8] = 返回值
    195b:   48 c7 40 08 00 00 00    movq   $0x0,0x8(%rax)            # M[返回值+8] = 0
    1962:   00

# ------------------------------------------------------------

    1963:   bd 05 00 00 00          mov    $0x5,%ebp                 # rbp = 5
    1968:   eb 09                   jmp    1973 <phase_6+0xf5>

    196a:   48 8b 5b 08             mov    0x8(%rbx),%rbx            # rbx = M[rbx+8]
    196e:   83 ed 01                sub    $0x1,%ebp                 # rbp -= 1
    1971:   74 11                   je     1984 <phase_6+0x106>      # if rbp = 1

                                                                     # rbx此时仍指向node_num1
    1973:   48 8b 43 08             mov    0x8(%rbx),%rax            # 返回值 = node_num1.nextNode
    1977:   8b 00                   mov    (%rax),%eax               # 返回值 = node_num2.number
    1979:   39 03                   cmp    %eax,(%rbx)
    197b:   7e ed                   jle    196a <phase_6+0xec>       # 要求node_num1.number <= node_num2.number
    197d:   e8 85 02 00 00          callq  1c07 <explode_bomb>
    1982:   eb e6                   jmp    196a <phase_6+0xec>

    1984:   48 8b 44 24 58          mov    0x58(%rsp),%rax
    1989:   64 48 2b 04 25 28 00    sub    %fs:0x28,%rax
    1990:   00 00
    1992:   75 0d                   jne    19a1 <phase_6+0x123>
    1994:   48 83 c4 60             add    $0x60,%rsp
    1998:   5b                      pop    %rbx
    1999:   5d                      pop    %rbp
    199a:   41 5c                   pop    %r12
    199c:   41 5d                   pop    %r13
    199e:   41 5e                   pop    %r14
    19a0:   c3                      retq
    19a1:   e8 aa f8 ff ff          callq  1250 <__stack_chk_fail@plt>
```

由于代码较长，我们把代码拆成4个关键部分来看。

1. `189e`~`18f4`部分：检查`num1`~`num6`是否符合约束条件

把`num1`~`num6`依次压入栈后，有一个双层循环。简化后的伪代码如下：

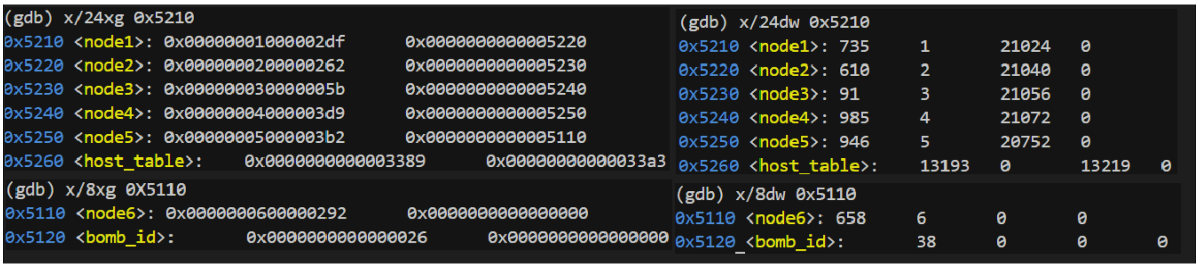
```
r14 = 1,
r13 = &num1
loop{
    rbp = r13
    要求 (r13) ∈ [1, 6]
    if r14 >= 6:
        break

    rbx = r14
    innerLoop{
        要求 (rbp) != num_(rbx+1) //下标为rbx+1
        rbx++
        if rbx >= 6:
            r14++
            r13 移向下一个数字
            continue loop
        else:
            continue innerLoop
    }
}
```

`r14`控制外层循环，遍历`[1,5]`，同时`r13`遍历`&num1`到`&num6`；`rbx`控制内层循环，遍历`[r14,5]`。可以推断出：

- `num1`~`num6`的取值为`[1,6]`。
- `num1`~`num6`互不相同。

2. `18fb`~`1927`部分：按一定顺序往栈里存放`node`对象的首地址

这部分中有关一个结构体。检查对象`node1`的位置`0x5210`附近并以不同格式打印，得到：



```
(gdb) x/24xg 0x5210
0x5210 <node1>: 0x00000001000002df      0x0000000000005220
0x5220 <node2>: 0x0000000200000262      0x0000000000005230
0x5230 <node3>: 0x000000030000005b      0x0000000000005240
0x5240 <node4>: 0x00000004000003d9      0x0000000000005250
0x5250 <node5>: 0x00000005000003b2      0x0000000000005110
0x5260 <host_table>:    0x0000000000003389      0x00000000000033a3
(gdb) x/8xg 0X5110
0x5110 <node6>: 0x0000000600000292      0x0000000000000000
0x5120 <bomb_id>:       0x0000000000000026      0x0000000000000000
```

```
(gdb) x/24dw 0x5210
0x5210 <node1>: 735     1       21024   0
0x5220 <node2>: 610     2       21040   0
0x5230 <node3>: 91      3       21056   0
0x5240 <node4>: 985     4       21072   0
0x5250 <node5>: 946     5       20752   0
0x5260 <host_table>:    13193   0       13219   0
(gdb) x/8dw 0x5110
0x5110 <node6>: 658     6       0       0
0x5120 <bomb_id>:       38      0       0       0
```

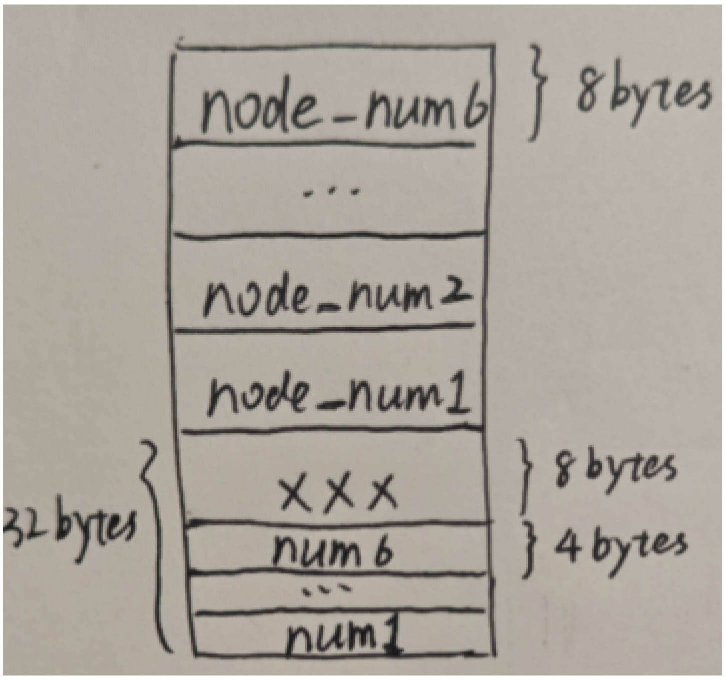
可以判断这是结构体对象，包含成员参数：4字节的数字`number`，4字节的数字`index`，以及8字节的地址`nextNode`指向下一个`node`的首地址。

在这段代码中，`arg2`遍历`[0,5]`，同时`arg4`遍历`num1`到`num6`，伪代码如下：

```
arg2 = 0
// arg2遍历[0,5]  num_(arg2+1) 遍历 num_1,..., num_6
loop{
    ret = 1
    arg3 = &node1
    if num_(arg2+1) == 1
        栈帧[32 + 8*arg2] = arg3
        arg2 ++
    else
        innerLoop{
            arg3指向下一个node
            ret ++  // ret与arg3所指的node的序号相同
            if ret != num_(arg2+1)
                continue innerLoop
        }
        // 此时ret = num_(arg2+1)，即arg3指向node_num_(arg2+1)
        栈帧[32 + 8*arg2] = arg3
        arg2 ++

    if arg2 == 6
        break
}
```

可见，这部分目的是为了按一定顺序往栈里存放`node`对象的首地址。要注意到，**`ret`与`arg3`所指的`node`的序号相同**。因此压栈的时候，`arg3`指向的其实是`node_num_(arg2+1)`。

所以`node`对象首地址在栈内的存储顺序从小地址到大地址其实是`node_num1`，`node_num2`，...，`node_num6`，栈内存储内容如图：



3. `1929`~`195b`部分：给`node_num1`~`node_num6`做"首尾相连"

如这部分反汇编代码中的注释，这一部分很显然是在给`node_num1`~`node_num6`做"首尾相连"，让`node_num_i.nextNode = node_num_(i+1)`。

4. `1963`~`197b`部分：检查`node_num_i.number`是否满足大小关系

如这部分反汇编代码中的注释，这一部分要求`node_num1.number <= node_num2.number`，以此类推。而根据内存中已知信息，`number`属性从小到大排序为`node3，node2，node6，node1，node5，node4`，其中`3 2 6 1 5 4`对应着`num1 num2 ... num6`。

因此答案为`3 2 6 1 5 4`。

secret_phase

1. 触发`secret_phase()`函数

阅读`phase_defused()`

```
0000000000001db0 <phase_defused>:
    1db0:   f3 0f 1e fa             endbr64
    1db4:   48 83 ec 78             sub    $0x78,%rsp
    1db8:   64 48 8b 04 25 28 00    mov    %fs:0x28,%rax
    1dbf:   00 00
    1dc1:   48 89 44 24 68          mov    %rax,0x68(%rsp)
    1dc6:   31 c0                   xor    %eax,%eax
    1dc8:   83 3d 21 39 00 00 06    cmpl   $0x6,0x3921(%rip)        # 56f0 <num_input_strings>      # 如果已经解开了六个炸弹（即已经输入了六个字符串）
    1dcf:   74 15                   je     1de6 <phase_defused+0x36>    # 意味着有资格进入隐藏关
    1dd1:   48 8b 44 24 68          mov    0x68(%rsp),%rax              # 否则退出phase_defused()，继续其他炸弹
    1dd6:   64 48 2b 04 25 28 00    sub    %fs:0x28,%rax
    1ddd:   00 00
    1ddf:   75 73                   jne    1e54 <phase_defused+0xa4>
    1de1:   48 83 c4 78             add    $0x78,%rsp
    1de5:   c3                      retq

    1de6:   48 8d 4c 24 0c          lea    0xc(%rsp),%rcx
    1deb:   48 8d 54 24 08          lea    0x8(%rsp),%rdx
    1df0:   4c 8d 44 24 10          lea    0x10(%rsp),%r8           # arg3,4,5分别为栈[8,12,16]
    1df5:   48 8d 35 7d 15 00 00    lea    0x157d(%rip),%rsi        # 3379 <array.0+0x199>      # "%d %d %s"
    1dfc:   48 8d 3d ed 39 00 00    lea    0x39ed(%rip),%rdi        # 57f0 <input_strings+0xf0> # 从该地址获得输入放进rdi，其实是phase_4的输入地址
    1e03:   e8 f8 f4 ff ff          callq  1300 <__isoc99_sscanf@plt>
    1e08:   83 f8 03                cmp    $0x3,%eax
    1e0b:   74 0e                   je     1e1b <phase_defused+0x6b># 确保输入三个元素就跳转
    1e0d:   48 8d 3d a4 14 00 00    lea    0x14a4(%rip),%rdi        # 32b8 <array.0+0xd8>
    1e14:   e8 07 f4 ff ff          callq  1220 <puts@plt>          # 没找到隐藏关，那就恭喜后结束
    1e19:   eb b6                   jmp    1dd1 <phase_defused+0x21># 做好善后工作，退出phase_defused

    1e1b:   48 8d 7c 24 10          lea    0x10(%rsp),%rdi          # arg1 指向 栈顶+16 = &arg5
    1e20:   48 8d 35 5b 15 00 00    lea    0x155b(%rip),%rsi        # 3382 <array.0+0x1a2>  # arg2 = &DrEvil
    1e27:   e8 c7 fc ff ff          callq  1af3 <strings_not_equal>
    1e2c:   85 c0                   test   %eax,%eax
    1e2e:   75 dd                   jne    1e0d <phase_defused+0x5d># 若arg5不是DrEvil，那就不进入隐藏关卡
    1e30:   48 8d 3d 21 14 00 00    lea    0x1421(%rip),%rdi        # 3258 <array.0+0x78>
    1e37:   e8 e4 f3 ff ff          callq  1220 <puts@plt>          # 输出找到隐藏
关的话语
    1e3c:   48 8d 3d 3d 14 00 00    lea    0x143d(%rip),%rdi        # 3280
<array.0+0xa0>
    1e43:   e8 d8 f3 ff ff          callq  1220 <puts@plt>          # 输出找到隐藏
关的话语
    1e48:   b8 00 00 00 00          mov    $0x0,%eax
    1e4d:   e8 95 fb ff ff          callq  19e7 <secret_phase>      # 传送进隐藏关
    1e52:   eb b9                   jmp    1e0d <phase_defused+0x5d>
    1e54:   e8 f7 f3 ff ff          callq  1250 <__stack_chk_fail@plt>
```

关键之处：

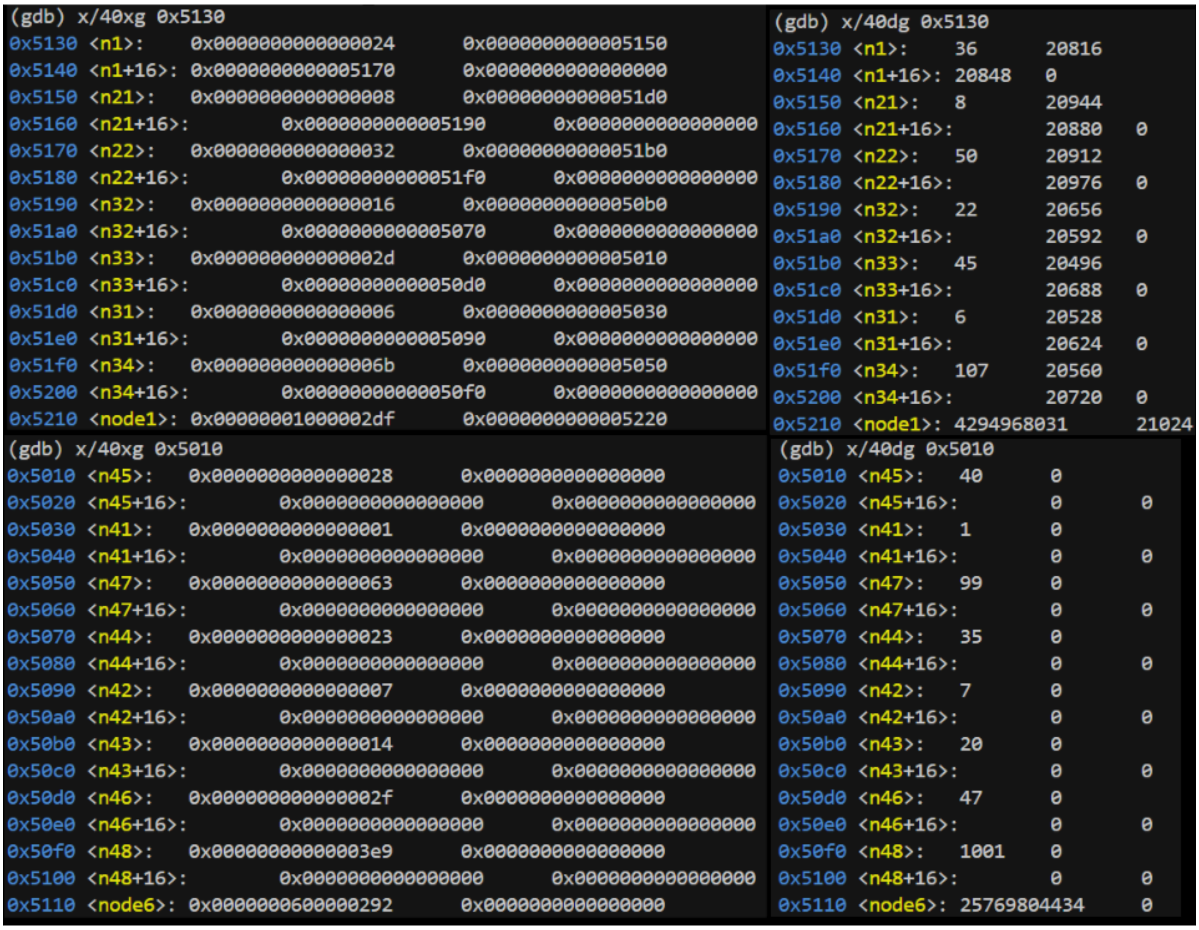
- 从地址`0x57f0`得到`sscanf`的第一个参数，这个参数的形式为两个整数和一个字符串，而这个地址不是全局变量的地址，而是某个用户输入处的地址。
- 从地址`0x3382`得到字符串应该为`DrEvil`。

运行`bomb38`，完成`phase_6`退出程序后，输入`x/s 0x5555555597f0（0x57f0链接后的地址）`，得到字符串`"4 19"`，正好是`phase_4`的输入。于是在其后面追加字符串`DrEvil`，即进入`secret_phase`。

2. 解secret_phase

```
00000000000019e7 <secret_phase>:
    19e7:   f3 0f 1e fa             endbr64
    19eb:   53                      push   %rbx
    19ec:   e8 87 02 00 00          callq  1c78 <read_line>
    19f1:   48 89 c7                mov    %rax,%rdi            # arg1 = readline
返回值，即我们输入
    19f4:   ba 0a 00 00 00          mov    $0xa,%edx            # arg3 = 10
    19f9:   be 00 00 00 00          mov    $0x0,%esi            # arg4 = 0
    19fe:   e8 dd f8 ff ff          callq  12e0 <strtol@plt>
    # long strtol(const char *str, char **endptr, int base), endptr值由函数设置为
str 中数值后的下一个字符
    1a03:   89 c3                   mov    %eax,%ebx            # rbx = 返回值，即
输入的字符串转化为的long型数
    1a05:   83 e8 01                sub    $0x1,%eax            # 返回值 -= 1
    1a08:   3d e8 03 00 00          cmp    $0x3e8,%eax
    1a0d:   77 26                   ja     1a35 <secret_phase+0x4e> # 要求输入的数
1 <= x <= 1001
    1a0f:   89 de                   mov    %ebx,%esi                # arg2 = 输入
的数
    1a11:   48 8d 3d 18 37 00 00    lea    0x3718(%rip),%rdi        # 5130 <n1> #
arg1 = &n1
    1a18:   e8 89 ff ff ff          callq  19a6 <fun7>
    1a1d:   83 f8 04                cmp    $0x4,%eax
    1a20:   75 1a                   jne    1a3c <secret_phase+0x55> # 要求fun7返回
值为4
    1a22:   48 8d 3d 5f 17 00 00    lea    0x175f(%rip),%rdi        # 3188
<_IO_stdin_used+0x188>    # 输出
    1a29:   e8 f2 f7 ff ff          callq  1220 <puts@plt>
    1a2e:   e8 7d 03 00 00          callq  1db0 <phase_defused>
    1a33:   5b                      pop    %rbx
    1a34:   c3                      retq
    1a35:   e8 cd 01 00 00          callq  1c07 <explode_bomb>
    1a3a:    eb d3                   jmp    1a0f <secret_phase+0x28>
    1a3c:    e8 c6 01 00 00          callq  1c07 <explode_bomb>
    1a41:    eb df                   jmp    1a22 <secret_phase+0x3b>
```

我们可以发现这一阶段要求我们输入一个介于`[1,1001]`整数，它将被转换为`long`类型后传入`fun7()`，而一并被传入的还有结构体对象`n1`。我们要输入的数字即为满足`fun7(n1, x) = 4`的解。仍然以不同格式打印`0x5130`附近的值，看到：



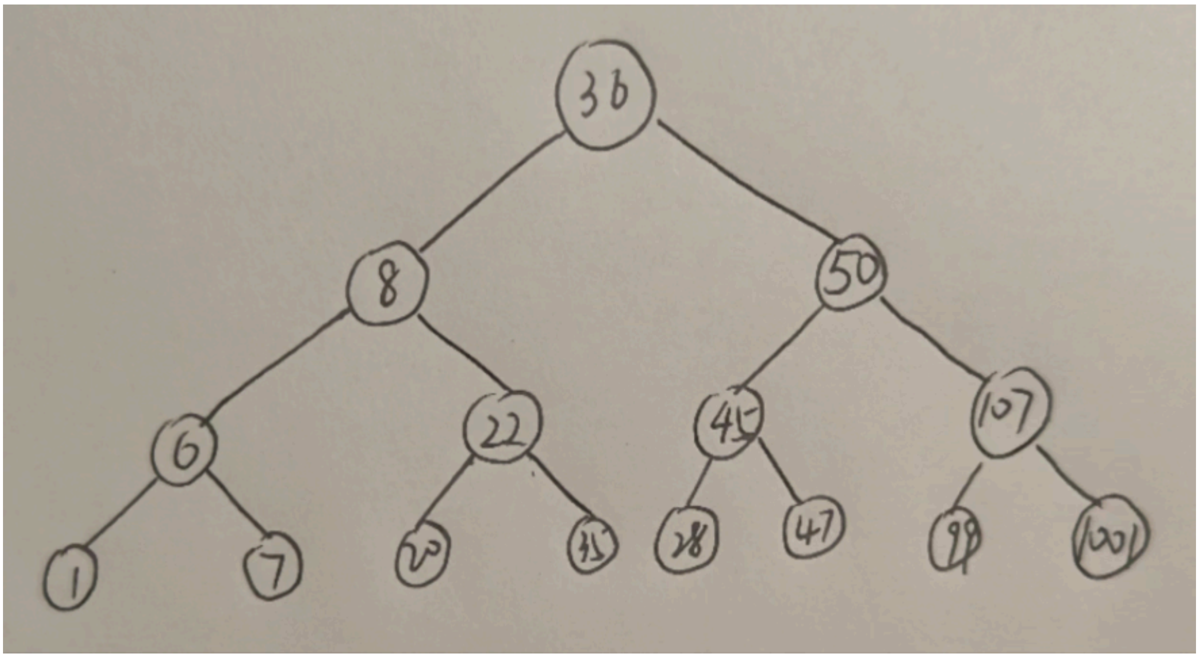
```
(gdb) x/40xg 0x5130
0x5130 <n1>:    0x0000000000000024      0x0000000000005150
0x5140 <n1+16>: 0x0000000000005170      0x0000000000000000
0x5150 <n21>:   0x0000000000000008      0x00000000000051d0
0x5160 <n21+16>:        0x0000000000005190      0x0000000000000000
0x5170 <n22>:   0x0000000000000032      0x00000000000051b0
0x5180 <n22+16>:        0x00000000000051f0      0x0000000000000000
0x5190 <n32>:   0x0000000000000016      0x00000000000050b0
0x51a0 <n32+16>:        0x0000000000005070      0x0000000000000000
0x51b0 <n33>:   0x000000000000002d      0x0000000000005010
0x51c0 <n33+16>:        0x00000000000050d0      0x0000000000000000
0x51d0 <n31>:   0x0000000000000006      0x0000000000005030
0x51e0 <n31+16>:        0x0000000000005090      0x0000000000000000
0x51f0 <n34>:   0x000000000000006b      0x0000000000005050
0x5200 <n34+16>:        0x00000000000050f0      0x0000000000000000
0x5210 <node1>: 0x00000001000002df      0x0000000000005220
```

```
(gdb) x/40dg 0x5130
0x5130 <n1>:    36      20816
0x5140 <n1+16>: 20848   0
0x5150 <n21>:   8       20944
0x5160 <n21+16>:        20880   0
0x5170 <n22>:   50      20912
0x5180 <n22+16>:        20976   0
0x5190 <n32>:   22      20656
0x51a0 <n32+16>:        20592   0
0x51b0 <n33>:   45      20496
0x51c0 <n33+16>:        20688   0
0x51d0 <n31>:   6       20528
0x51e0 <n31+16>:        20624   0
0x51f0 <n34>:   107     20560
0x5200 <n34+16>:        20720   0
0x5210 <node1>: 4294968031      21024
```

```
(gdb) x/40xg 0x5010
0x5010 <n45>:   0x0000000000000028      0x0000000000000000
0x5020 <n45+16>:        0x0000000000000000      0x0000000000000000
0x5030 <n41>:   0x0000000000000001      0x0000000000000000
0x5040 <n41+16>:        0x0000000000000000      0x0000000000000000
0x5050 <n47>:   0x0000000000000063      0x0000000000000000
0x5060 <n47+16>:        0x0000000000000000      0x0000000000000000
0x5070 <n44>:   0x0000000000000023      0x0000000000000000
0x5080 <n44+16>:        0x0000000000000000      0x0000000000000000
0x5090 <n42>:   0x0000000000000007      0x0000000000000000
0x50a0 <n42+16>:        0x0000000000000000      0x0000000000000000
0x50b0 <n43>:   0x0000000000000014      0x0000000000000000
0x50c0 <n43+16>:        0x0000000000000000      0x0000000000000000
0x50d0 <n46>:   0x000000000000002f      0x0000000000000000
0x50e0 <n46+16>:        0x0000000000000000      0x0000000000000000
0x50f0 <n48>:   0x00000000000003e9      0x0000000000000000
0x5100 <n48+16>:        0x0000000000000000      0x0000000000000000
0x5110 <node6>: 0x0000000600000292      0x0000000000000000
```

```
(gdb) x/40dg 0x5010
0x5010 <n45>:   40      0
0x5020 <n45+16>:        0       0
0x5030 <n41>:   1       0
0x5040 <n41+16>:        0       0
0x5050 <n47>:   99      0
0x5060 <n47+16>:        0       0
0x5070 <n44>:   35      0
0x5080 <n44+16>:        0       0
0x5090 <n42>:   7       0
0x50a0 <n42+16>:        0       0
0x50b0 <n43>:   20      0
0x50c0 <n43+16>:        0       0
0x50d0 <n46>:   47      0
0x50e0 <n46+16>:        0       0
0x50f0 <n48>:   1001    0
0x5100 <n48+16>:        0       0
0x5110 <node6>: 25769804434     0
```

可见这是一个占据32字节的结构体，起名为`TreeNode`，包含的成员参数有8字节的`long number`，8字节的`TreeNode *leftNode`，8字节的`TreeNode *rightNode`，以及8字节用于对齐的无用参数。我们可以据此画出一棵树。



阅读 `fun7()`：

```
00000000000019a6 <fun7>:
    # 从始至终：arg2 = 输入的数
    19a6:   f3 0f 1e fa             endbr64
    19aa:   48 85 ff                test   %rdi,%rdi
    19ad:   74 32                   je     19e1 <fun7+0x3b>     # 确保传入的不是空地址
    19af:   48 83 ec 08             sub    $0x8,%rsp
    19b3:   8b 17                   mov    (%rdi),%edx          # arg3 = 结点
    19b5:   39 f2                   cmp    %esi,%edx
    19b7:   7f 0c                   jg     19c5 <fun7+0x1f>     # if arg3.number > arg2, goto .L0
    19b9:   b8 00 00 00 00          mov    $0x0,%eax            # 返回值 = 0
    19be:   75 12                   jne    19d2 <fun7+0x2c>     # if arg3.number != arg2即<, goto .L1
#.L2:
    19c0:   48 83 c4 08             add    $0x8,%rsp
    19c4:   c3                      retq                        # 递归出口：arg3.number == arg2
#.L0:
    19c5:   48 8b 7f 08             mov    0x8(%rdi),%rdi       # arg1 = *arg1的左子node
    19c9:   e8 d8 ff ff ff          callq  19a6 <fun7>          # fun7()
    19ce:   01 c0                   add    %eax,%eax            # eax = 2eax
    19d0:   eb ee                   jmp    19c0 <fun7+0x1a>     # goto .L2,即返回了
#.L1:
    19d2:   48 8b 7f 10             mov    0x10(%rdi),%rdi      # arg1 = *arg1的右子node
    19d6:   e8 cb ff ff ff          callq  19a6 <fun7>          # fun7()
    19db:   8d 44 00 01             lea    0x1(%rax,%rax,1),%eax# 返回值 = 返回值*2+1
    19df:   eb df                   jmp    19c0 <fun7+0x1a>     # goto .L2.即返回了
    19e1:   b8 ff ff ff ff          mov    $0xffffffff,%eax     # 返回失败值-1
    19e6:   c3                      retq
```

据此可以简单写出伪代码：

```
int fun7(TreeNode *node, long arg2){    // arg2 = 输入的1-1001之间的数
    if(*node.num > arg2){
        arg1 = *node.leftNode;
        ret = fun7(arg1, arg2);
        ret = ret * 2;
        return ret;
    }else if(*node.num < arg2){
        ret = 0;
        arg1 = *node.rightNode;
        ret = fun7(arg1, arg2);
        ret = ret * 2 + 1;
        return ret;
    }else{
        return 0;
    }
}
```

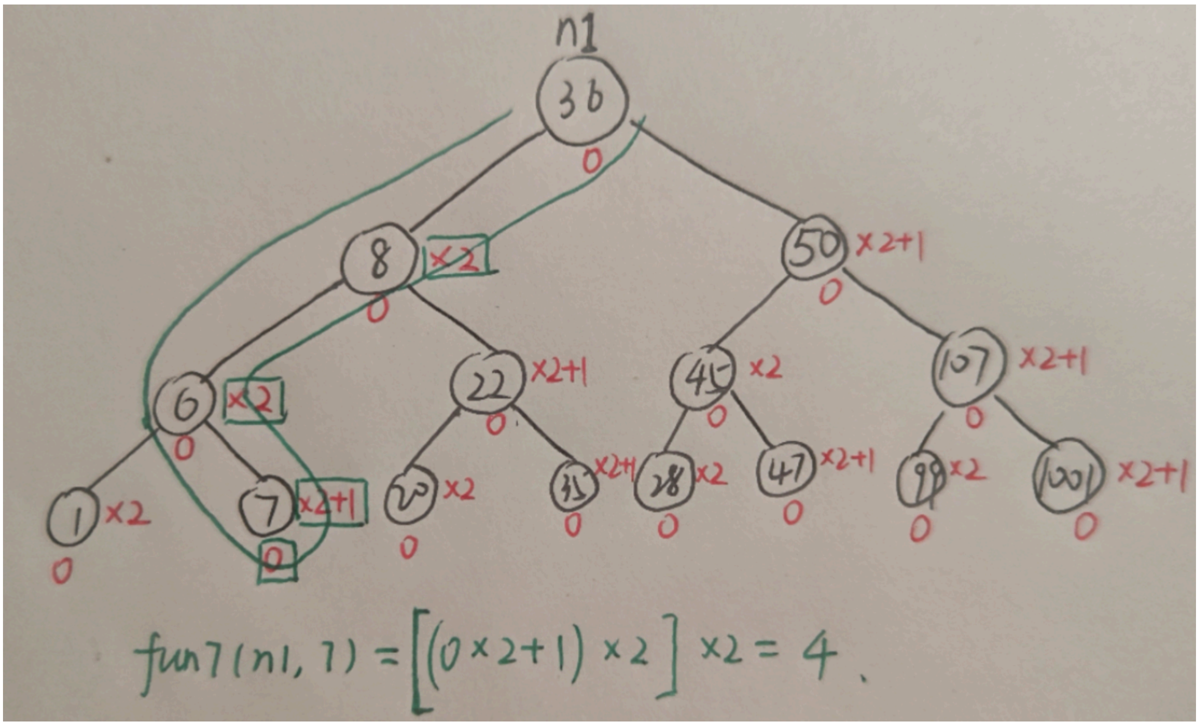
这是一个递归程序，其返回值与`arg2`有关。显然，**只有当`arg2`是树中某个结点的值，函数才能正确返回。**

如何求出各个`fun7(n1, x)`的值？

我们在画出的树的结点下侧和右侧做标记。结点`childnode`下侧的数表示调用`fun7(childnode, *childnode.num)`返回的值，显然都是`0`，而右侧的数表示`fun7(childnode, *childnode.num)`返回后要对返回值继续做的操作：

- 如果这个结点是左子结点，返回值`*2`；
- 如果这个结点是右子结点，返回值`*2+1`。

例如，`fun7(n1, 7)`的返回值可以按下图方式计算：



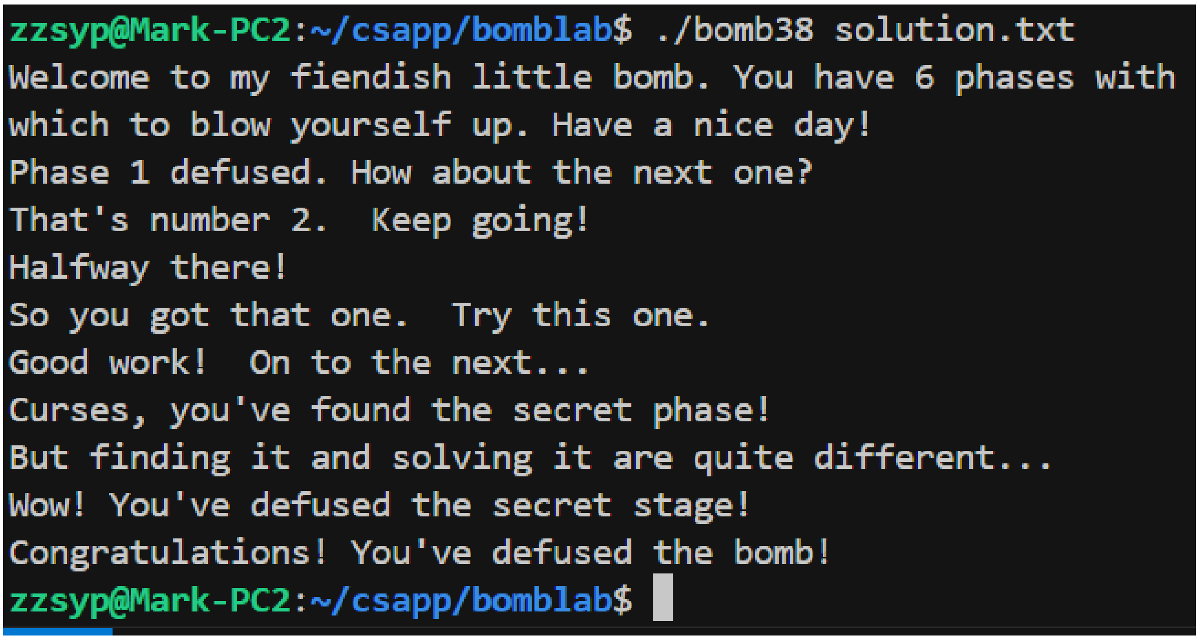
可以按照此方式计算出当`x=树中结点的数`，`fun7(n1,x)`的值。那显然，我们要输入的数字正是`7`。

四、实验结果

solution.txt的内容为：

```
Border relations with Canada have never been better.
1 2 4 7 11 16
6 895
4 19 DrEvil
5 115
3 2 6 1 5 4
7

```

运行结果：



```
zzsyp@Mark-PC2:~/csapp/bomblab$ ./bomb38 solution.txt
Welcome to my fiendish little bomb. You have 6 phases with
which to blow yourself up. Have a nice day!
Phase 1 defused. How about the next one?
That's number 2.  Keep going!
Halfway there!
So you got that one.  Try this one.
Good work!  On to the next...
Curses, you've found the secret phase!
But finding it and solving it are quite different...
Wow! You've defused the secret stage!
Congratulations! You've defused the bomb!
zzsyp@Mark-PC2:~/csapp/bomblab$
```