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CSE543
Introduction to Computer and Network Security
Module: Program Vulnerabilities

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Programming

- Why do we write programs?
  - Function
- What functions do we enable via our programs?
  - Some we want -- some we don't need
  - Adversaries take advantage of such "hidden" function

Some Attack Categories

- Control-flow Attacks
  - Adversary directs program control-flow
    - E.g., return address overwrite through buffer overflow
- Data Attacks
  - Adversary exploits flaw to read/modify unexpected data
    - E.g., critical variable overwrite through buffer overflow
- Code Injection Attacks
  - Adversary tricks the program into executing their input
    - E.g., SQL injection attacks
- Other types of attacks on unauthorized access (later)
- See CWE (http://cwe.mitre.org/)

Memory Errors

- Many attacks are possible because some programming languages allow memory errors
  - C and C++ for example
- A memory error occurs when the program allows an access to a variable to read/write to memory beyond what is allocated to that variable
  - E.g., read/write beyond the end of a string
  - Access memory next to the string
- Memory errors may be exploited to change the program's control-flow or data-flow or to allow injection of code

A Simple Program

```
void myfunc()
{
    char string[16];
    printf("Enter a string\n");
    scanf(“%s”, string);
    printf(“You entered: %s\n”, string);
}
int main()
{
    myfunc();
}
```

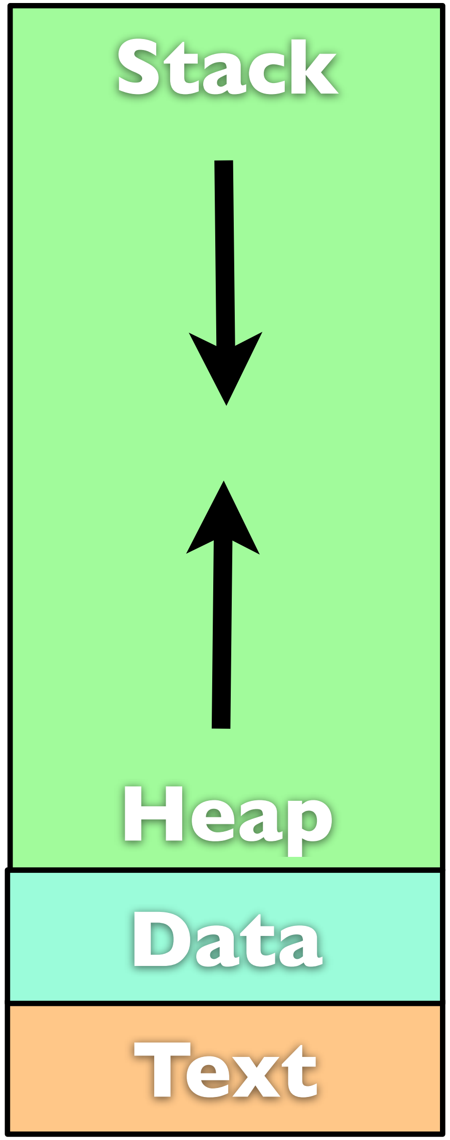
```
root@newyork:~/test# ./a.out
Enter a string
mystring
You entered: mystring
```

```
root@newyork:~/test# ./a.out
Enter a string
ajhsoieurhgeskljdfghkljghsdjfhgsldkjfghskljrhgfdkj
You entered: ajhsoieurhgeskljdfghkljghsdjfhgsldkjfghskljrhgfdkj
Segmentation fault (core dumped)
```

What Happened?

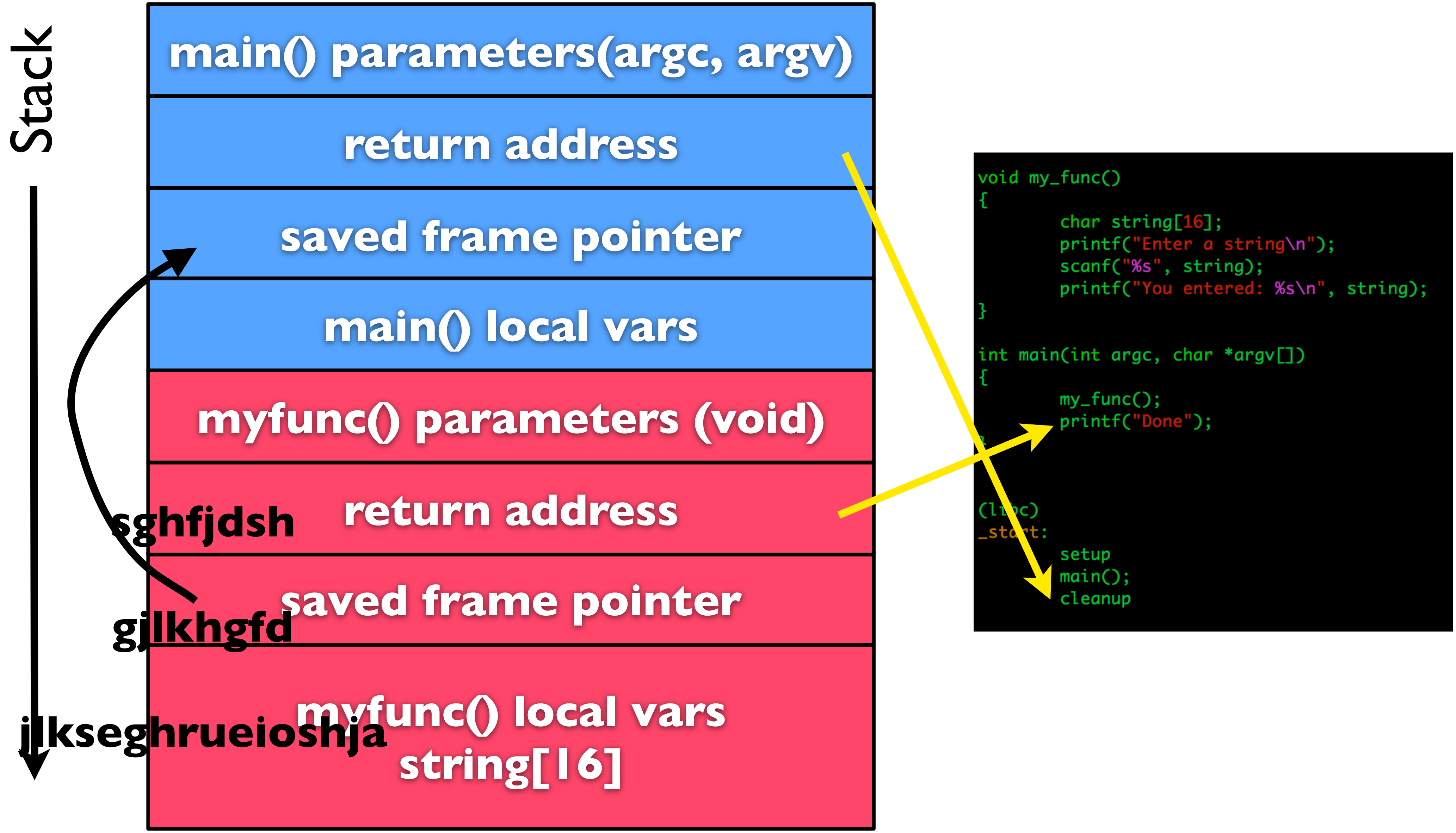
- Brief refresher on program address space
  - Stack -- local variables
  - Heap -- dynamically allocated (malloc, free)
  - Data -- global, uninitialized variables
  - Text -- program code

```
root@newyork:~/test# cat /proc/self/maps
08048000-08053000 r-xp 00000000 08:01 131088     /bin/cat
08053000-08054000 r--p 0000a000 08:01 131088     /bin/cat
08054000-08055000 rw-p 0000b000 08:01 131088     /bin/cat
08c20000-08c41000 rw-p 00000000 00:00 0          [heap]
b7352000-b7552000 r--p 00000000 08:01 10346      /usr/lib/locale/locale-archive
b7552000-b7553000 rw-p 00000000 00:00 0
b7553000-b7700000 r-xp 00000000 08:01 122        /lib/i386-linux-gnu/libc-2.17.so
b7700000-b7702000 r--p 001ad000 08:01 122        /lib/i386-linux-gnu/libc-2.17.so
b7702000-b7703000 rw-p 001af000 08:01 122        /lib/i386-linux-gnu/libc-2.17.so
b7703000-b7706000 rw-p 00000000 00:00 0
b770d000-b770f000 rw-p 00000000 00:00 0
b770f000-b7710000 r-xp 00000000 00:00 0          [vdso]
b7710000-b7730000 r-xp 00000000 08:01 102        /lib/i386-linux-gnu/ld-2.17.so
b7730000-b7731000 r--p 0001f000 08:01 102        /lib/i386-linux-gnu/ld-2.17.so
b7731000-b7732000 rw-p 00020000 08:01 102        /lib/i386-linux-gnu/ld-2.17.so
bfea2000-bfec3000 rw-p 00000000 00:00 0          [stack]
```



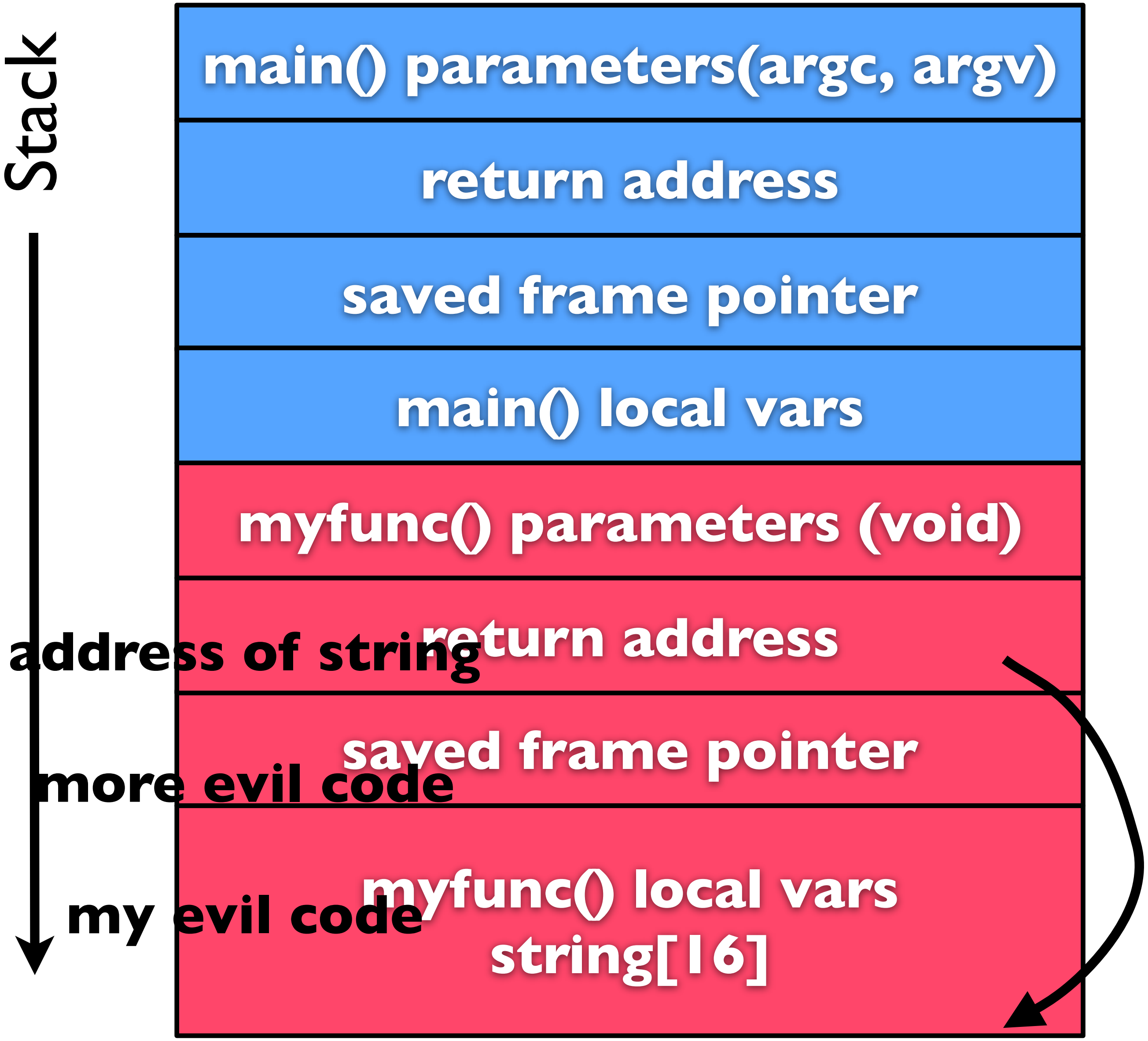
What Happened?

- Stack Layout



Exploiting Buffer Overflow

- Stack Layout

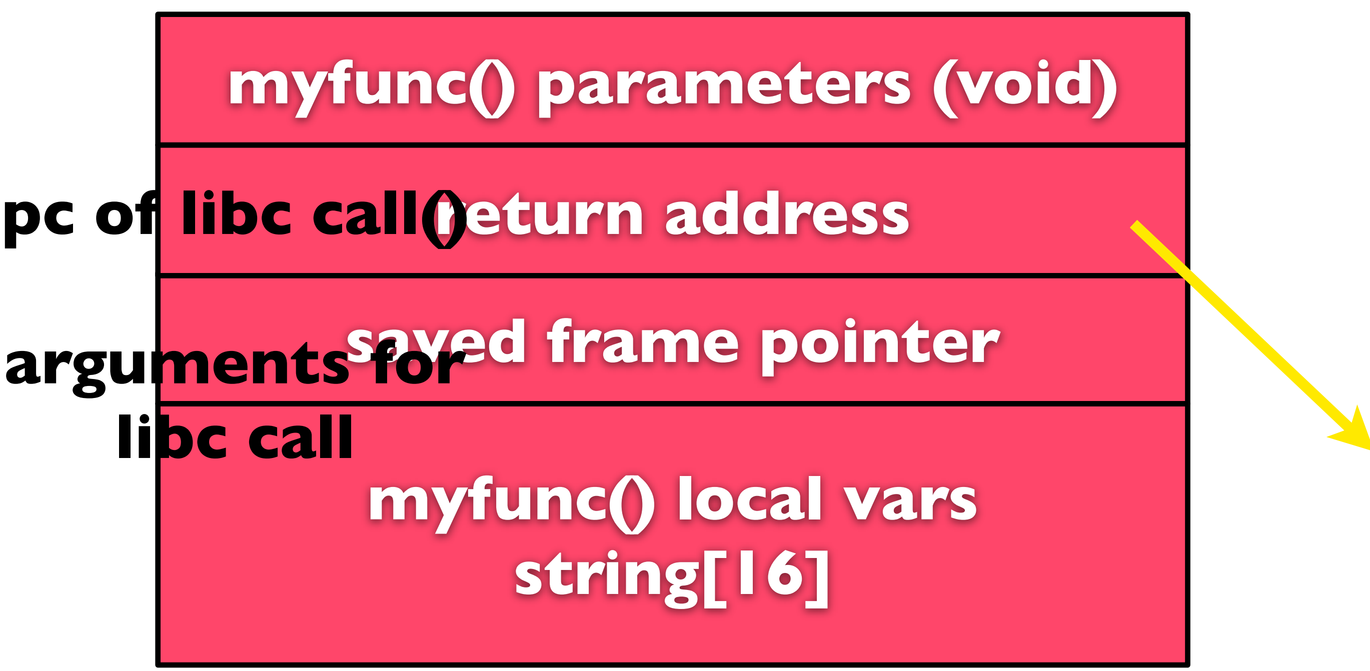



```
void my_func()
{
        char string[16];
        printf("Enter a string\n");
        scanf("%s", string);
        printf("You entered: %s\n", string);
}

int main(int argc, char *argv[])
{
        my_func();
        printf("Done");
}


(libc)
_start:
        setup
        main();
        cleanup
```

Prevent Code Injection

- What if we made the stack non-executable?
  - AMD NX-bit
  - More general: W (xor) X (DEP in Windows)

```
root@newyork:~/test# cat /proc/self/maps
08048000-08053000 r-xp 00000000 08:01 131088
08053000-08054000 r--p 0000a000 08:01 131088
08054000-08055000 rw-p 0000b000 08:01 131088
08c20000-08c41000 rw-p 00000000 00:00 0
b7352000-b7552000 r--p 00000000 08:01 10346
b7552000-b7553000 rw-p 00000000 00:00 0
b7553000-b7700000 r-xp 00000000 08:01 122
b7700000-b7702000 r--p 001ad000 08:01 122
b7702000-b7703000 rw-p 001af000 08:01 122
b7703000-b7706000 rw-p 00000000 00:00 0
b770d000-b770f000 rw-p 00000000 00:00 0
b770f000-b7710000 r-xp 00000000 00:00 0
b7710000-b7730000 r-xp 00000000 08:01 102
b7730000-b7731000 r--p 0001f000 08:01 102
b7731000-b7732000 rw-p 00020000 08:01 102
bfea2000-bfec3000 rw-p 00000000 00:00 0
```




```
(libc)

int system(const char *command)
{
        ...
}
```

Protect the Return Address

- "Canary" on the stack
  - Random value placed between the local vars and the return address
  - If canary is modified, program is stopped
- Have we solved buffer overflows?

Canary Shortcomings

- Other local variables?
- Frame pointers?
- Anything left unprotected on stack can be used to launch attacks
- Not possible to protect everything
  - Varargs
  - Structure members
  - Performance

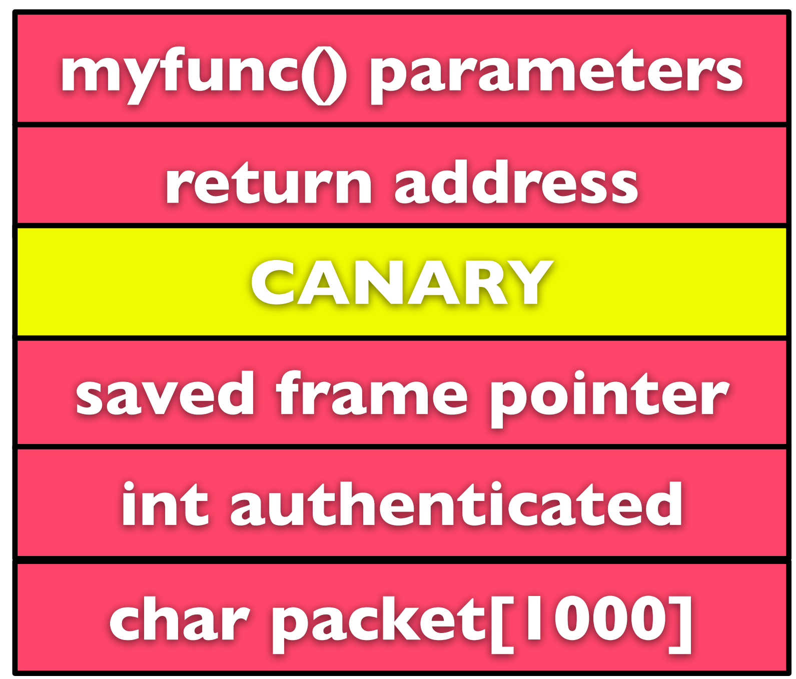
A Simple Program

```
int authenticated = 0;
char packet[1000];

while (!authenticated) {
  PacketRead(packet);
  if (Authenticate(packet))
    authenticated = 1;
}
 if (authenticated)
   ProcessPacket(packet);
```

A Simple Program

```
int authenticated = 0;
char packet[1000];

while (!authenticated) {
  PacketRead(packet);
  if (Authenticate(packet))
    authenticated = 1;
}
 if (authenticated)
   ProcessPacket(packet);
```

What if packet is only 1004 bytes?



Overflow of Local Variables

- Don't need to modify return address
  - Local variables may affect control
- What kinds of local variables would impact control?
  - Ones used in conditionals (example)
  - Function pointers
- What can you do to prevent that?

A Simple Program

```
int authenticated = 0;
char *packet = (char *)malloc(1000);

while (!authenticated) {
  PacketRead(packet);
  if (Authenticate(packet))
    authenticated = 1;
}
 if (authenticated)
   ProcessPacket(packet);
```

What if we allocate the packet buffer on the heap?

Heap Overflows

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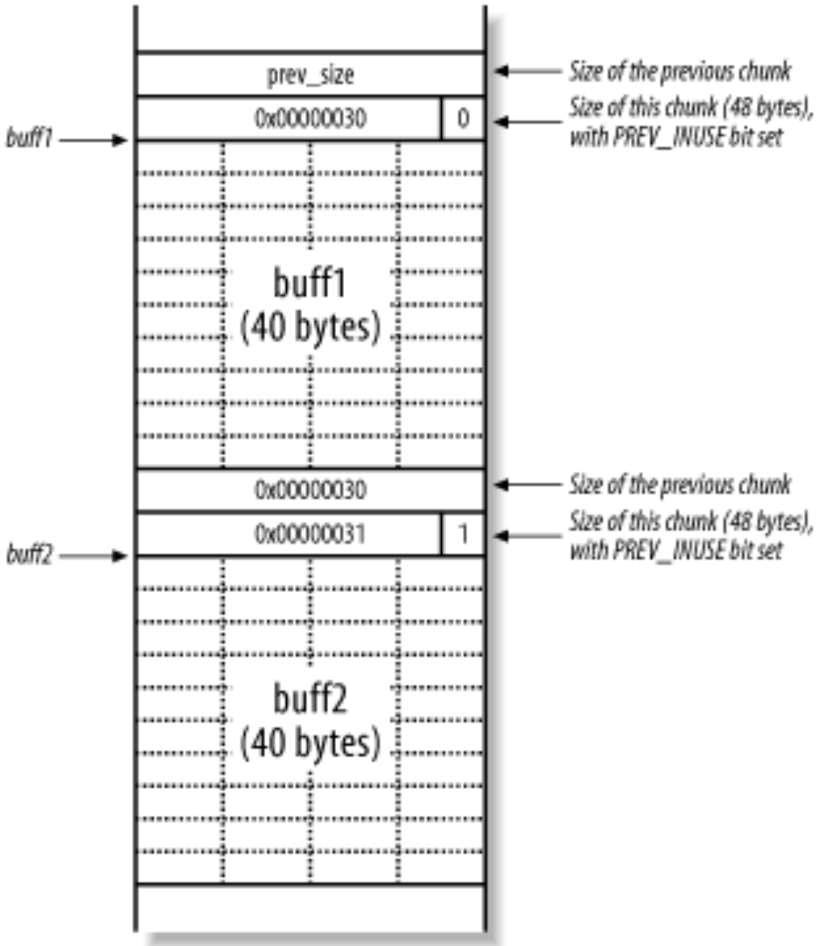
- Overflows on heap also possible

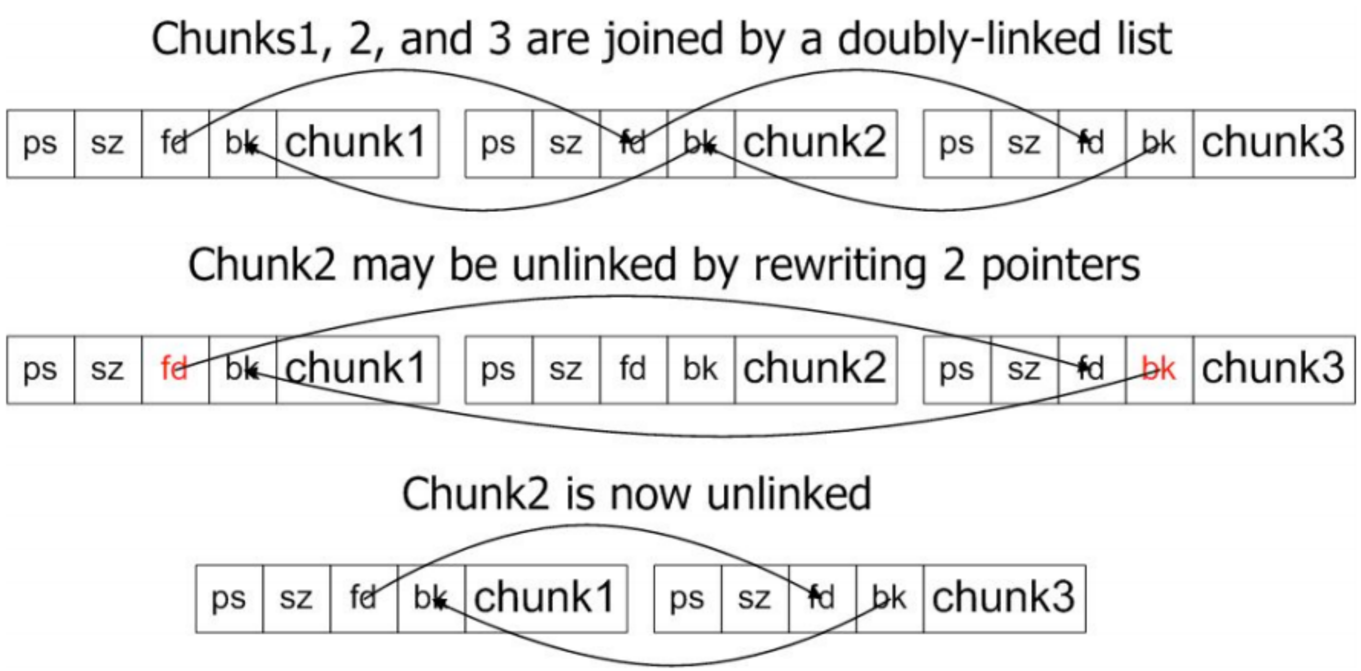
```
char *packet = malloc(1000)
packet[1000] = 'M';
```

- "Classical" heap overflow corrupts metadata
  - Heap metadata maintains chunk size, previous and next pointers, ...
    - Heap metadata is *inline* with heap data
  - And waits for heap management functions (**malloc, free**) to write corrupted metadata to target locations



Heap Overflows

- Heap allocators maintain a doubly-linked list of allocated and free chunks
- **`malloc`**() and **`free`**() modify this list



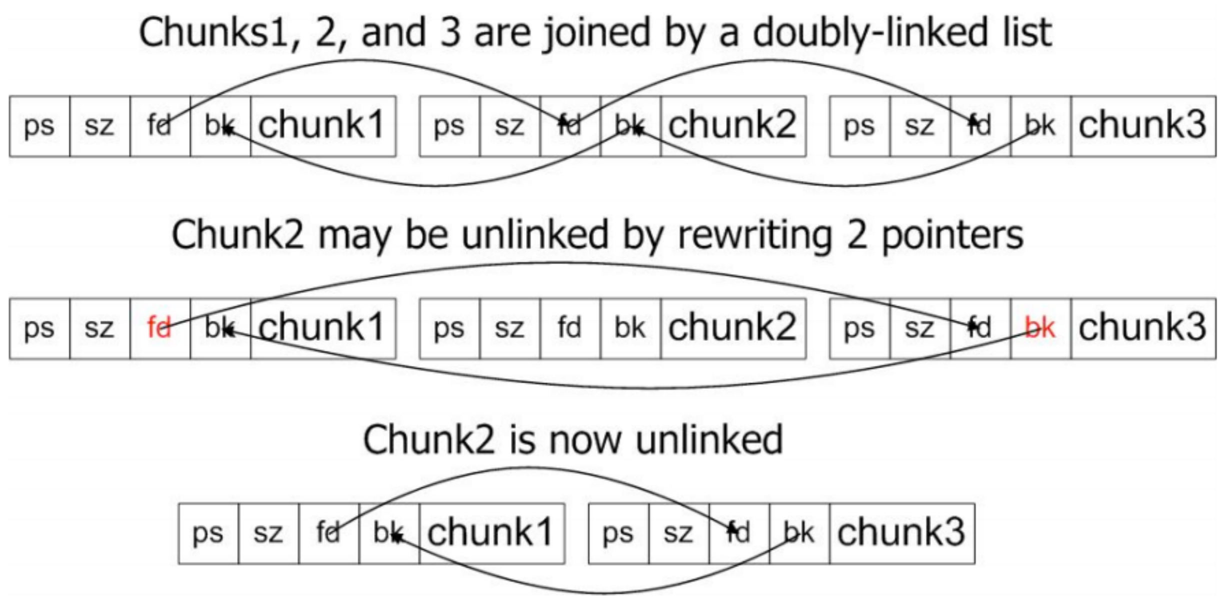
- http://www.sans.edu/student-files/presentations/heap_overflows_notes.pdf

Heap Overflows

- free() removes a chunk from allocated list

```
chunk2->bk->fd = chunk2->fd
chunk2->fd->bk = chunk2->bk
```

- By overflowing chunk2, attacker controls bk and fd
  - Controls both *where* and *what* data is written!
    - Arbitrarily change memory (e.g., function pointers)

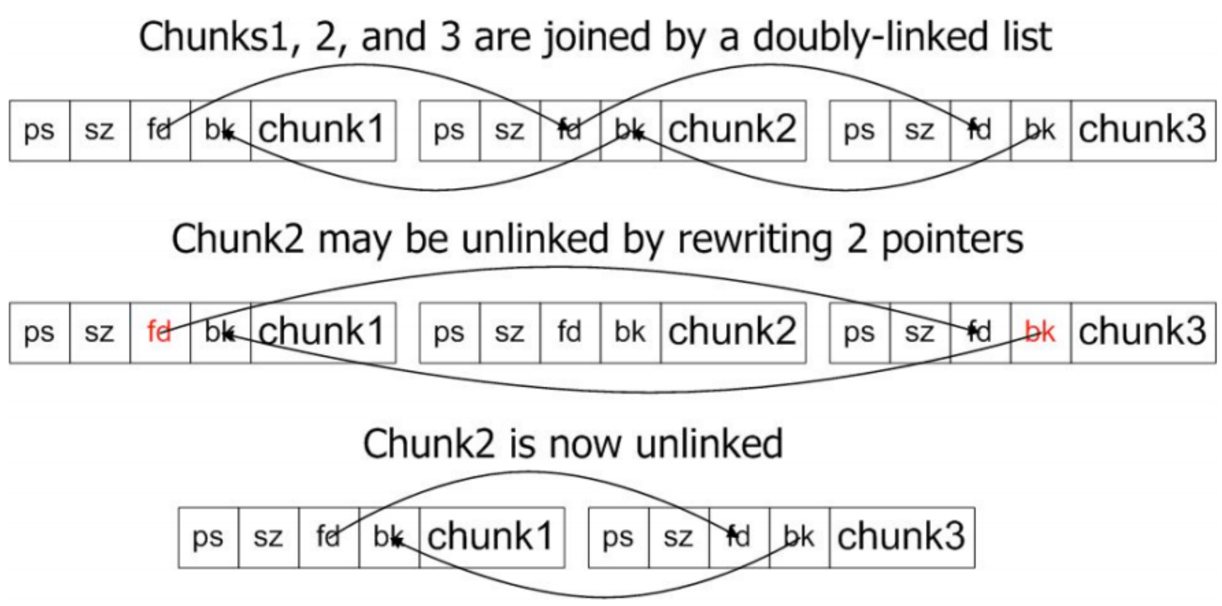


Heap Overflows

- free() removes a chunk from allocated list

```
chunk2->bk->fd = chunk2->fd     v[chunk1+8]= chunk3
chunk2->fd->bk = chunk2->bk     v[chunk3+12] = chunk1
```

- By overflowing chunk2, attacker controls bk and fd
  - Controls both *where* and *what* data is written!
    - Arbitrarily change memory (e.g., function pointers)



Heap Overflows

- By overflowing chunk2, attacker controls bk and fd
  - Controls both *where* and *what* data is written!
    - Assign chunk2->fd to value to want to write
    - Assign chunk2->bk to address X (where you want to write)
      - Less an offset of the fd field in the structure
- Free() removes a chunk from allocated list

```
chunk2->bk->fd = chunk2->fd
chunk2->fd->bk = chunk2->bk
```

- What's the result?

Heap Overflows

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- By overflowing chunk2, attacker controls bk and fd
  - Controls both *where* and *what* data is written!
    - Assign chunk2->fd to value to want to write
    - Assign chunk2->bk to address X (where you want to write)
      - Less an offset of the fd field in the structure
- Free() removes a chunk from allocated list

```
chunk2->bk->fd = chunk2->fd
     addrX->fd = value
chunk2->fd->bk = chunk2->bk
     value->bk = addrX
```

```
chunk2->bk->fd = chunk2->fd
     => addrX+8 = value
   If adversary wants to write
   value 0xdeadbeef to address
      0xbffffffc, she writes
     chunk2->fd = 0xdeadbeef
   chunk2->bk = 0xbffffffc - 8
```

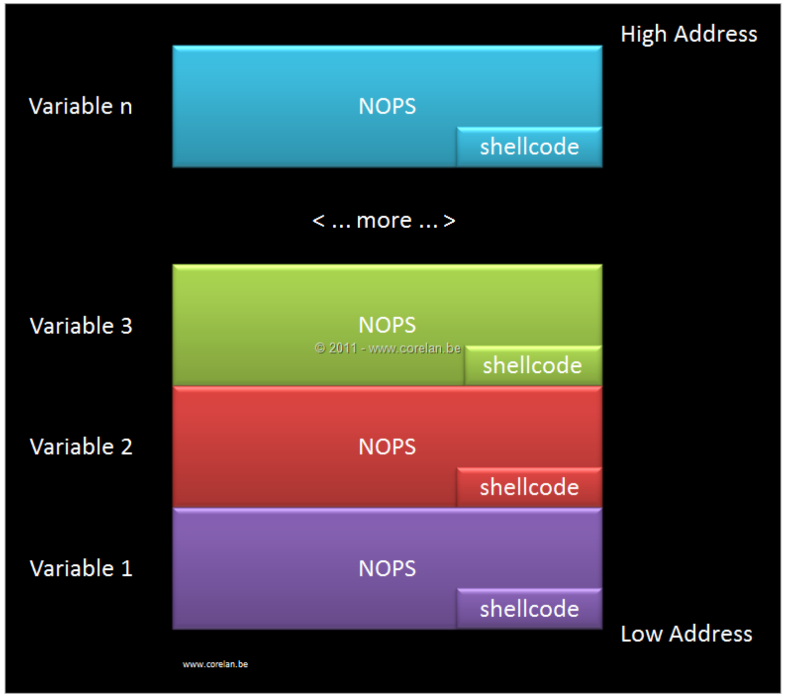
- What's the result?
  - Change a memory address to a new pointer value (in data)

Overflow Defenses

- Address space randomization
  - Make it difficult to predict where a particular program variable is stored in memory
- Rather than randomly locate every variable
  - A simpler solution is to randomly offset each memory region
- Address space layout randomization (ASLR)
  - Stack and heap are located at different base addresses each time the program is run
  - NOTE: Always on a page offset, however, so limited in range of bits available for randomization
- Also, works for buffer overflows

Other Heap Attacks

- Heap spraying
  - Combat randomization by filling heap with allocated objects containing malicious code
  - Use another vulnerability to overwrite a function pointer to any heap address, hoping it points to a sprayed object
  - Heuristic defenses
    - e.g., NOZZLE: If heap data is like code, flag attack
- Use-after-free
  - Type confusion



Heap Overflow Defenses

- Separate data and metadata
  - e.g., OpenBSD's allocator (Variation of **`PHKmalloc`**)
- Sanity checks during heap management

```
free(chunk2) -->
    assert(chunk2->fd->bk == chunk2)
    assert(chunk2->bk->fd == chunk2)
```

  - Added to GNU **`libc`** 2.3.5
- Randomization
- Q. *What are analogous defenses for stack overflows?*

Another Simple Program

```
int size = BASE_SIZE;
char *packet = (char *)malloc(1000);
char *buf = (char *)malloc(1000+BASE_SIZE);

 strcpy(buf, FILE_PREFIX);
 size += PacketRead(packet);
 if (size >= 1000+BASE_SIZE)) {
   return(-1)
 }
 else
   strcat(buf, packet);
   fd = open(buf);
 }
```

Any problem with this conditional check?

Integer Overflow

- Signed variables represent positive and negative values
  - Consider an 8-bit integer: -128 to 127
  - Weird math: *127+1 = ???*
- This results in some strange behaviors
  - `size += PacketRead(packet)`
    - What is the possible value of size?
  - `if ( size >= 1000+BASE_SIZE ) … {`
    - What is the possible result of this condition?
- How do we prevent these errors?

Another Simple Program

```
int size = BASE_SIZE;
char *packet = (char *)malloc(1000);
char *buf = (char *)malloc(1000+BASE_SIZE);

 strcpy(buf, FILE_PREFIX);
 size += PacketRead(packet);
 if ( size < 1000+BASE_SIZE) {
   strcat(buf, packet);
   fd = open(buf);
   printf(packet);
 }
```

Any problem with this printf?

Format String Vulnerability

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- Attacker control of the format string results in a format string vulnerability
  - printf is a very versatile function
    - %s - dereferences (crash program)
      - printf("Hello %s"); //expects 2 args
    - %x - print addresses (leak addresses, break ASLR)
      - printf("Hello %x %x %x"); // expects 4 arguments
    - %n - write to address (arbitrarily change memory)
      - printf ("12345%n", &x); // writes 5 into x
- Never use
  - **`printf(string);`**
- Instead, use

Take Away

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- Programs have function
  - Adversaries can exploit unexpected functions
- Vulnerabilities due to malicious input
  - Subvert control-flow or critical data
    - Buffer, heap, integer overflows, format string vulnerabilities
  - Injection attacks
    - Application-dependent
- If applicable, write programs in languages that eliminate classes of vulnerabilities
  - E.g., Type-safe languages such as Java